I.FAST

Innovation Fostering in Accelerator Science and Technology

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MILESTONE REPORT

First Plasma achieved on the prototype

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ABSTRACT

The development of the internal RF Ion Source for Cyclotrons concept and the development of a first prototype of this ion source is described. The document presents also the first results of the prototype installed on the updated Ion Source Test Bench (IST) in CIEMAT, including visual check that the plasma is produced and the conditions for the start and stop of the plasma. Further work will include spectral analysis of the plasma, and extraction current measurements.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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Executive summary

The objective of WP12.3 is to design, fabricate and characterize a prototype of an RF Ion Source for Cyclotrons.

This type of Ion Source has the objective of being able to substitute Penning Ion sources in currently working or newly manufactured cyclotrons with the claimed possible advantages of lower cathode wear and better efficiency in terms of beam produced for each unit of hydrogen gas consumed.

The basic design of a prototype ion source following this concept for AMIT cyclotron was performed. An RF window was selected as the most adequate mechanism of coupling. With the help of RF and thermal simulations a 2.45 GHz quarter wave resonant cavity internal geometry was designed.

A detailed design of a completely compatible the AMIT cyclotron ion source, including this RF cavity inside was done. Its external geometry is exactly the same as AMIT's ion source.

The fabrication of the ion source, involving several steps was performed. The most critical one was the brazing of the basic structure of the ion source, composed of its two bodies, the flange and the water and hydrogen tubes between them. A relevant incident in the fabrication process was the incorrect brazing of one of the unions, leading to a reparation after a careful study of the possibilities.

The low power tests of the ion source showed a resonant frequency and quality factor similar to the ones from the simulations.

The Ion Source Test (IST) facility at CIEMAT was updated, with the most significant change being the modification of the extraction system from DC to RF. The new extraction system is based on a 60 MHz cavity completely constructed during this period. Its conditioning to about 16 % of its nominal value was completed.

Plasma has been produced in the ion source. The start and stop of the plasma are independent of the amount of hydrogen flow. Even with no flow, just with residual amounts of gas in the chamber the plasma can be started. This contrasts with the case of a conventional Penning ion source, which for a sustainable plasma needs a minimum amount of gas flowing into the chamber.

The plasma starts with an RF power on each of the two cavities of 70 W with 50% reflected power, corresponding to a cathode voltage of approximately 2 kV.

One the plasma has started, the RF power can be lowered to about 2W, corresponding to a voltage in the order of 400 V.

Further work is foreseen to characterize the plasma by analysing its visual range spectrum and to extract and measure beam current. The parameters to be modified during this characterization will be the RF power, the effect of having two or just one RF cavity working, the magnetic field of the dipole, the hydrogen gas flow and the cathode material (copper or tantalum).

1 Introduction

The typical ion source used in small to medium H^- cyclotrons, called Penning ion source, is based in a high voltage discharge between two cathodes located at both ends of the plasma column area and the anode, which is constituted by the cylindrical wall inside of which the plasma is produced. The magnetic field produced by the cyclotron confined the plasma in the transverse direction. Typically, a high voltage (2-3 kV) is needed for the start of the ion source. Once the plasma is produced the impact of positive ions on the cathodes heats them enhancing the thermionic electrons emission which helps maintaining the plasma with a much lower voltage, in the order of 200 V. This type of ion source is called to be of "cold cathode" type, since no method other than the bombardment of ions itself is used to heat the cathode.

These ion sources are widely used due to their compactness, simplicity, and their good stability in the ions current produced. They have though two main disadvantages: high cathode wears due to the sputtering produced by the ions impacting the cathode and bad efficiency in terms of beam produced for each unit of hydrogen flow injected into the ion source, leading to high hydrogen gas loss into the cyclotron vacuum chamber which negatively affects the vacuum pressure.

A new concept of ion source for small to medium cyclotrons is proposed, in which the high voltage is substituted with an RF voltage created in a resonant cavity. The typical configuration of many Penning ion sources, with a thin cathode suspending from one of its ends and creating the plasma on the other, makes it very convenient to convert its geometry into a quarter wave resonator, with the cathode acting as a stem, with a short circuit on one of its ends and an open circuit on the other in which the voltage for the plasma creation will be produced. See Figure 1.1, showing the AMIT cyclotron Penning ion source, in which it can be seen how its internal geometry resembles a quarter wave resonator on which the cathode acts as the stem.

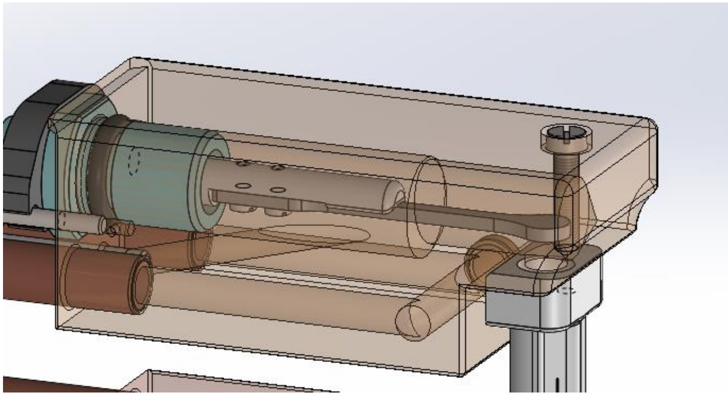


Figure 1.1 Penning ion source of AMIT cyclotron (the copper body of the ion source being shown as transparent)

This geometry similarities between a conventional Penning ion source and its adaptation to work with RF would make it relatively simple and cheap to adapt ion sources currently working on commercial cyclotrons to this RF concept in case some of the advantages claimed makes it worthwhile.

If the voltage creating the plasma is an RF voltage instead of a DC one, the cathode would no longer have a negative voltage bias (indeed, it should not be called cathode anymore) attracting the positive ions, and the RF currents would heat the cathode, thus increasing the thermionic electrons emission without the need for impacting ions heating the cathode.

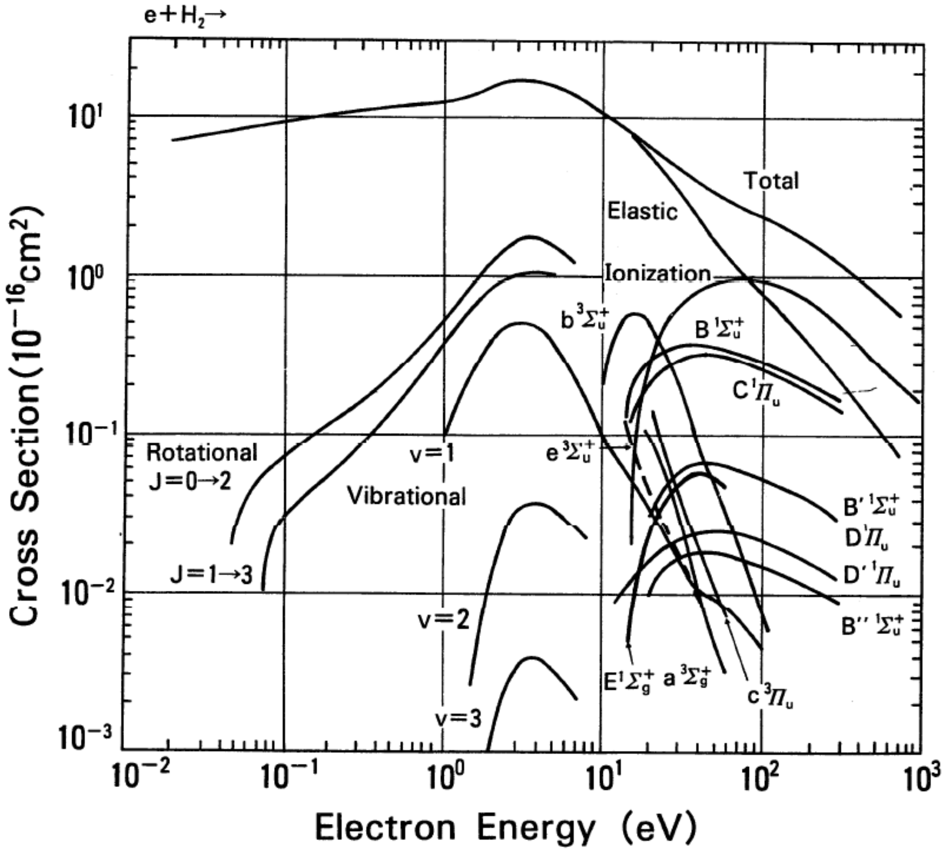
The idea for this ion source is inspired in [1], where an RF generated plasma is maintained for a long time with no erosion of the copper layer of the PCB. This is because, by increasing the discharge frequency the voltage plasma-wall is reduced and the ions impacting the wall don't have enough kinetic energy for producing sputtering (rip out of atoms from the wall).

The design, fabrication, and test of an RF ion source (called IRISC: Internal Radiofrequency Ion Source for Cyclotrons) is based on the Penning ion source of the cyclotron AMIT and completely compatible with it. In this respect the IRISC ion source should have the same external geometry and the same slit in the chimney, so that the electric field in the centre zone of the cyclotron which extracts the beam from the ion source is the same for both types of ion sources. The dimensions of this ion source are especially suitable for using a frequency in the order of 2.5 GHz.

The objective is that due to the high RF frequency a capacitive discharge is created operating in a collision-less heating mode, in which electrons gain energy just in the plasma-wall region minimizing in this way the plasma potential. Once the discharge is established the RF frequency and RF power can be modified to get maximum electrons density.

This type of discharge avoids the presence of high energy electrons typically found in a conventional Penning ion source, which are accelerated by the high DC potential of this type of ion source. This fact is important because the main mechanism for production of H^- ions is the dissociative attachment, by which an electron impacts a H_2 molecule creating a H^- and a H^0 [2], see Figure 1.2. Although the cross section for this process has a maximum in the region 10-30 eV, there is also a resonance at low energy in which the cross section is increased in various orders of magnitude if the H_2 molecule is in an excited vibrational mode. The cross section for excited vibrational modes of H_2 molecule has a maximum in the area 1-10 eV. If we get a plasma in which all electrons have an energy of just some tens of eV we postulate that we should be able to efficiently generate H^-, without the presence of electrons of much higher energy that contribute only to their destruction.

A patent application has been registered for the concept of IRISC ion source [3]



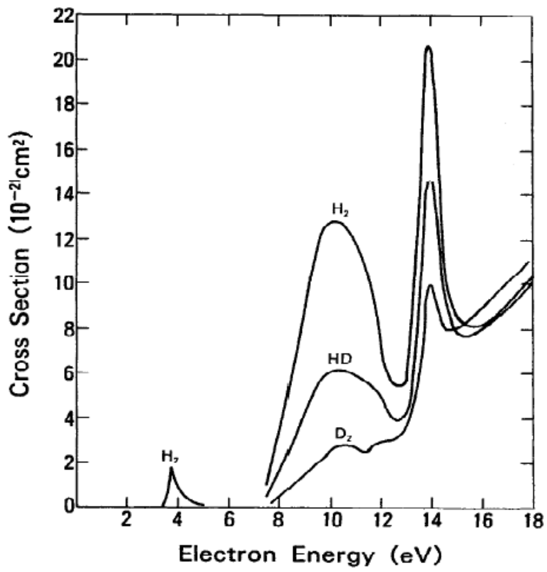


TABLE 2. Dissociative-attachment cross sections near thresholds for several vibrational levels[72a].

v	E(eV)	σ(cm^2)
0	3.75	2.8(− 21)
1	3.23	8.3(− 20)
2	2.75	1.0(− 18)
3	2.29	7.5(− 18)
4	1.86	3.8(− 17)
5	1.46	1.2(− 18)
6	1.08	2.9(− 18)
7	0.74	4.3(− 18)
8	0.42	3.2(− 18)
9	0.14	4.3(− 18)

[a] Note: 2.8(−21) means 2.8×10^{-21}.

Figure 1.2: Cross sections for various processes in e^- with H_2 collisions (up). Cross section for H^- production by dissociative attachment (down)

I.FAST task 12.3, with the participation of the CIEMAT institute, the Healthcare division of General Electric and the Cyclomed company, is divided in the packages shown in the following table, in which the involvement of each of the participants is detailed.

		CIEMAT	CYCLOMED	GENERAL ELECTRIC
WP1. Market analysis	• Definition of the market context of cyclotron with internal sources for industrial and clinical applications. • Identification of current and emerging key trends on internal ion sources • Internal ion sources benchmarking: SWOT definition		X	X
WP2. Detailed Ion Source design	• Design specification. • Prototype modelling and optimization with EM and plasma simulations	X	X	X
WP3. Prototype manufacturing & RF system specification	• Manufacturing and low power test. • Design, purchase and test of the RF power system.	X	X	
WP4. Prototype assembly and plasma measurements	• Prototype assembly at CIEMAT's Ion Source Test facility. • Plasma ignition and discharge characterization.	X		X
WP5. Beam extraction and characterization	• Extraction and characterization of ion beam. • Long-term studies of erosion and source lifetime.	X		X

2 Conceptual Design

The targets of the conceptual design of the prototype IRISC ion source were the following:

- To design an IRISC ion source completely compatible with the AMIT cyclotron ion source. Therefore, the external geometry of the ion source main bodies and the chimney should be identical to the AMIT cyclotron Penning ion source.
- To adapt the internal configuration of the cyclotron ion source to create a RF resonant cavity providing the voltage for the operation.
- To make the cavity as efficient as possible.
- To decide on the best coupling method for the transfer of RF power to the cavity
- To evaluate the temperatures achieved at the different parts of the ion source

For this task, RF and thermal simulations were performed using HFSS and Ansys Mechanical.

Three different coupling methods were considered: capacitive coupling, inductive coupling, and window coupling (see Figure 2.1), including HFSS simulations. Capacitive and inductive coupling were discarded because of their very small dimensions and complicated shape that would make them extremely difficult to fabricate and would create high local heating. The window coupling, consisting just in a wall with two slits in it separating the resonant RF quarter wave cavity from the coaxial line bringing the power in. The size if the slit is calibrated to get a coupling factor as close as possible to 1. The window coupling solution was selected because it is easier to manufacture, it is more appropriate taking into account the size of the cavity and fits especially well in the body of the ion source.

Regarding the cathode and the central area were the voltage creating the plasma is generated, an initial design with a bended cathode ("L" shaped) was considered (See Figure 2.2). The reason for using a bended cathode was to locate the cathode tip closer to the anode (chimney walls) so higher electric fields could be obtained for a given voltage. This solution was discarded for two reasons. One, difficulty in its fabrication and second and most important, the tip of the cathode has to confront the chimney drill in order to get a good electric field distribution at that area, but its position is sensible to fabrication and assembly errors of the cathode, which is assembled on its other end to the RF window.

Therefore, we decided to go for a flat cathode solution, making the electric field at the cathode tip area much less sensible to errors in the cathode tip position, and including a new part (called "insert") mounted on the chimney hole bringing the chimney walls potential closer to the cathode (see Figure 2.3). The insert not only helps getting a higher electric field for a given voltage, but also the size and location of its internal drill configures the plasma column dimensions and position. These parameters (especially the distance of the plasma border to the extraction slit) are critical for the extracted current of the ion source. So just by changing the small insert (a cheap and easy to manufacture part) we can modify the size and position of the plasma without the need to change more complicated parts like the cathodes or the chimney.

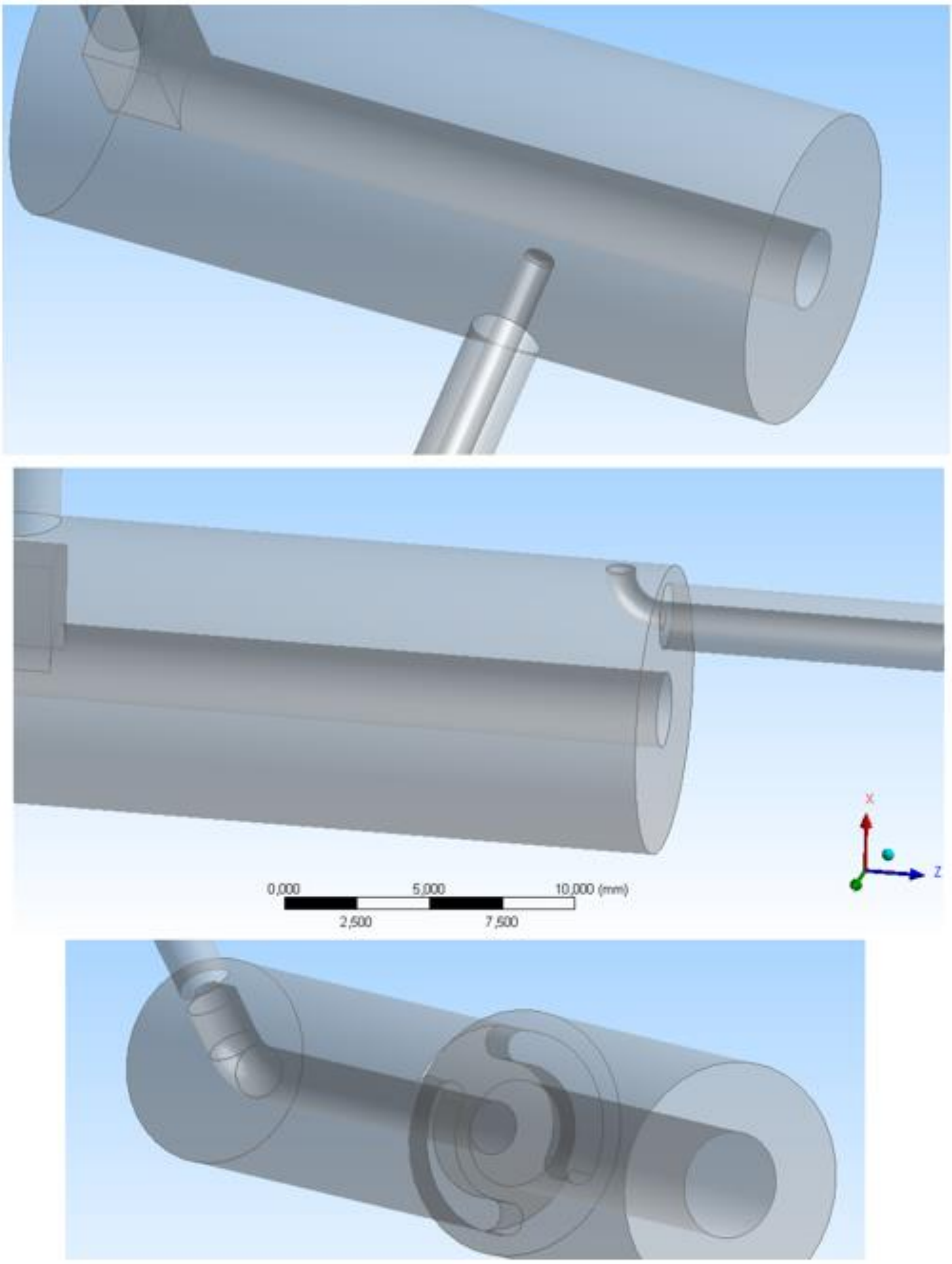


Figure 2.1: Geometries in HFSS of capacitive coupling (up), inductive coupling (center) and window coupling (bottom)

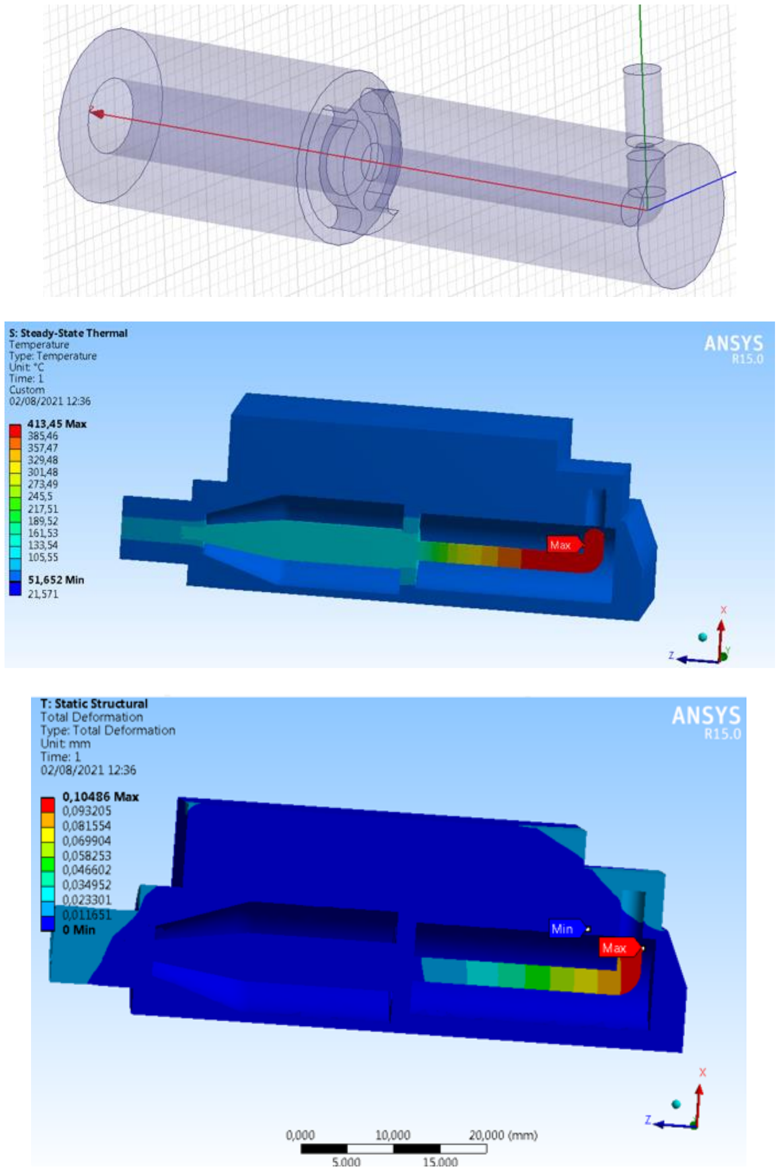


Figure 2.2: Bended cathode solution. HFSS model (up), temperatures simulation (center) and displacement simulation (down)

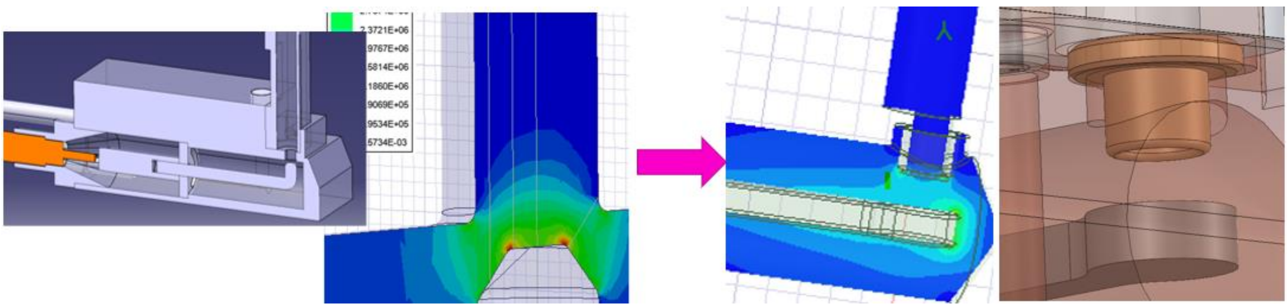


Figure 2.3: Initially considered geometry with a bended cathode (left) and finally selected solution with a flat cathode and an insert. For each solution the 3D model and the simulated electric field level are shown

The internal geometry of the ion source has been optimized by doing RF and thermal simulations. Figure 2.4 shows the electric and magnetic fields distribution for the final geometry. The electric field is concentrated at the tip of the cathode as desired, where we desire to create the plasma. The magnetic field is maximum at the other side of the cathode where the RF currents are greater.

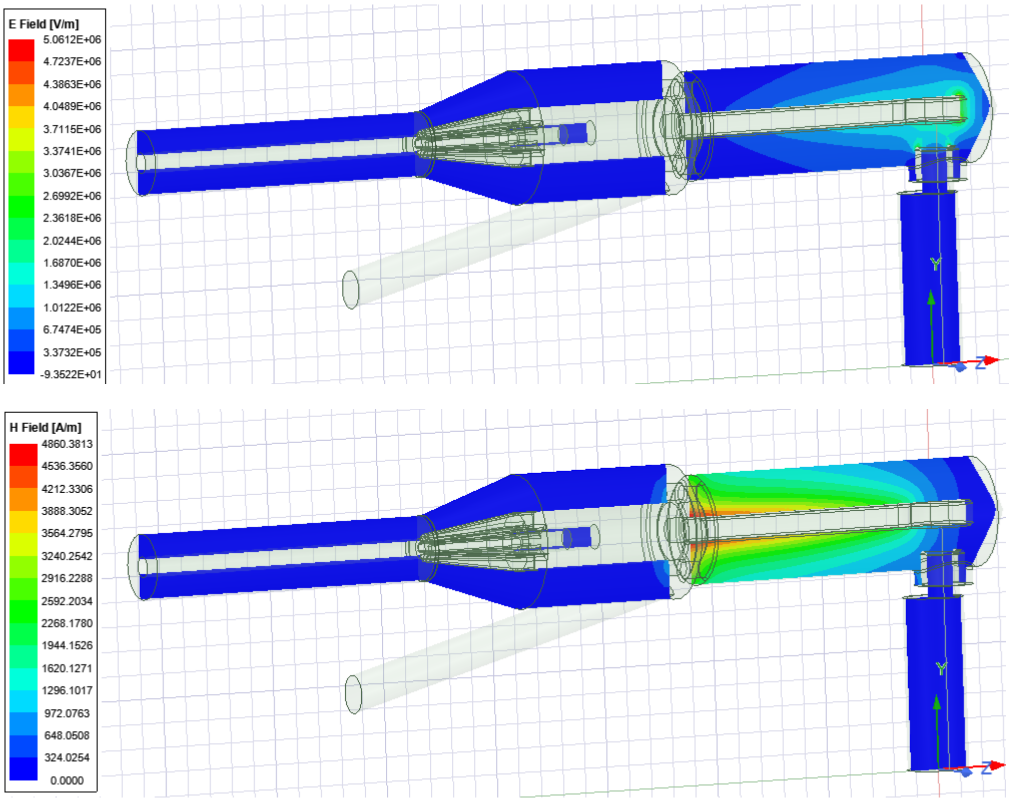


Figure 2.4: Calculated electric (up) and magnetic (down) RF fields for the final geometry. Normalize to 3 kV voltage at the tip of the cathode

Two materials for the cathodes are considered: copper and tantalum. They represent two extremes regarding cathode behaviour. Copper has a much higher electrical and thermal conductivity than tantalum, but much lower propension to thermionic electrons emission. Therefore, we expect the tantalum cathode to get a much higher temperature for a given RF voltage, with higher RF power loss and much more electrons emitted. The copper cathode, on the other side, should stay colder and emit fewer electrons. The simulations show an RF power loss (normalized to 3 kV voltage) of 74.4 W for the tantalum cathode and 34.27 W for the copper one.

Thermal simulations have been performed with the two materials, see Figure 2.5, showing the expected differences in temperature between them. The body of the ion source remains at the same temperature as the cooling water because it is a highly massive piece of copper with very good heat transmission properties. Basically, the only part that increases its temperature is the cathode because it is not directly cooled and must evacuate all its heat through its small section connection with the RF window. The tip of the cathode is therefore the hottest point, which is a good thing to produce plasma. The temperature increase (maximum temperature minus coolant temperature) is proportional to the RF power and thus proportional to the square of the voltage. In figure 2.6 the relationship between the RF voltage and the cathode tip temperature are shown.

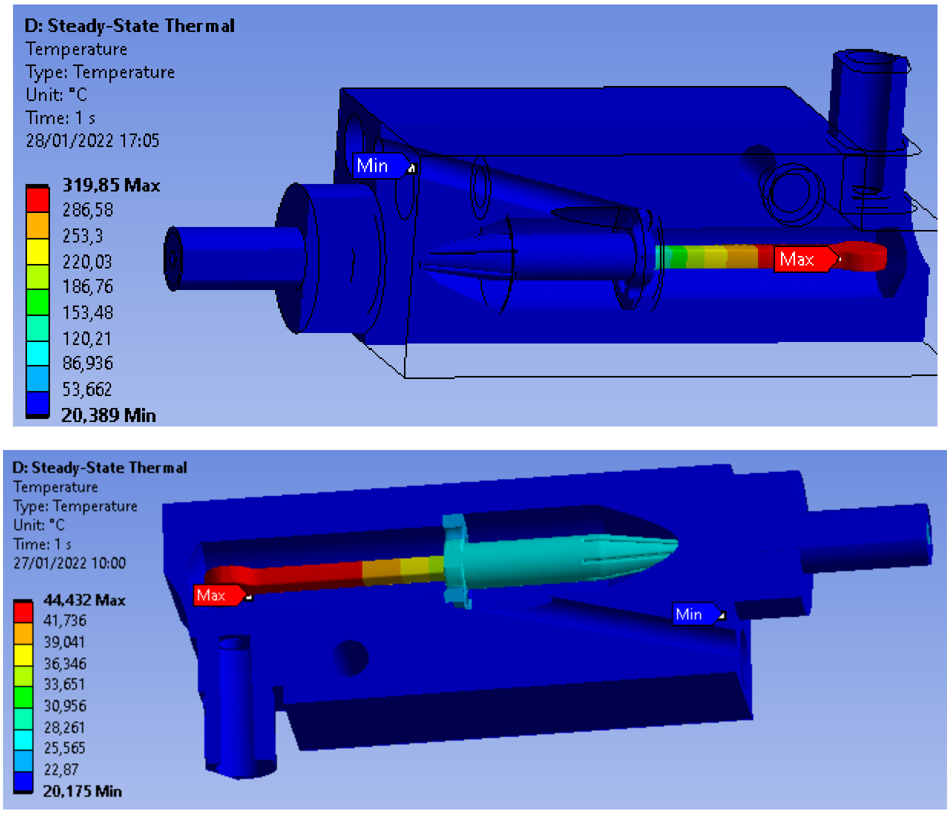


Figure 2.5. Temperature distribution, normalized to 1 kV voltage, at the tip of the cathode for tantalum cathode (up) and copper cathode (down)

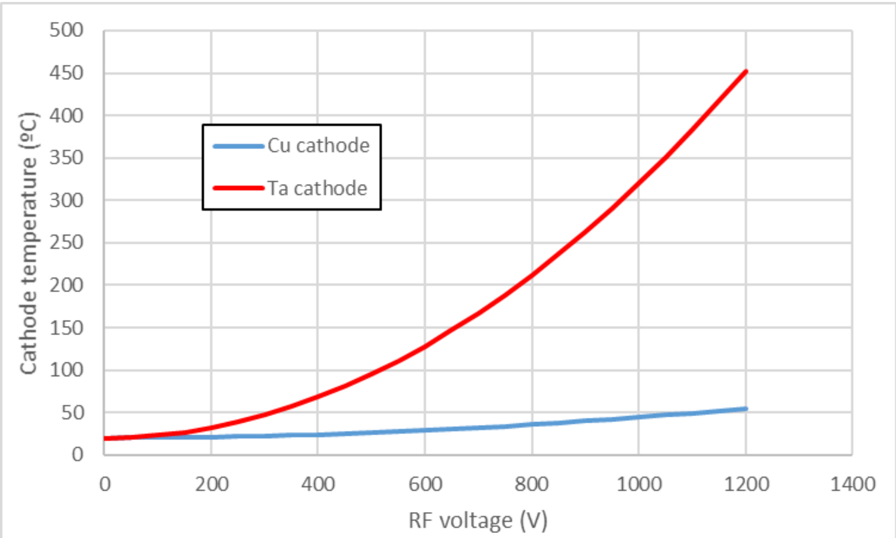


Figure 2.6: Relationship between ion source cavity voltage and expected temperature at the tip of the cathode (just the effect of the RF heating)

3 Detailed design

The detailed design of the IRISC ion source prototype had the following objectives:

- To make a specific design for the fabrication of a prototype following all the requirements of internal geometry and material properties derived from the conceptual design
- To make the ion source completely compatible mechanically and regarding the extraction field with the AMIT cyclotron, which means that the ion source bodies, and chimney should have exactly the same external geometry, their relative position with respect to the ion source flange should be exactly the same, and the flange should be compatible (bolts and O-ring position) with respect to the AMIT cyclotron original Penning ion source.
- To use materials and design manufacturing methods as reliable, simple, and cheap as possible.

A complete 3D model of the IRISC ion source was developed, see Figure 3.1. From that fabrication drawing for all the components and for the subassemblies, including a fabrication drawing for the brazing structure were developed. A total of 37 fabrication drawings were done.

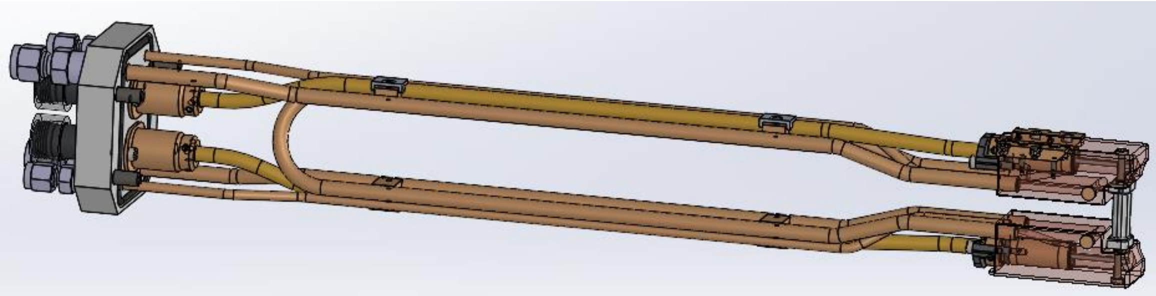
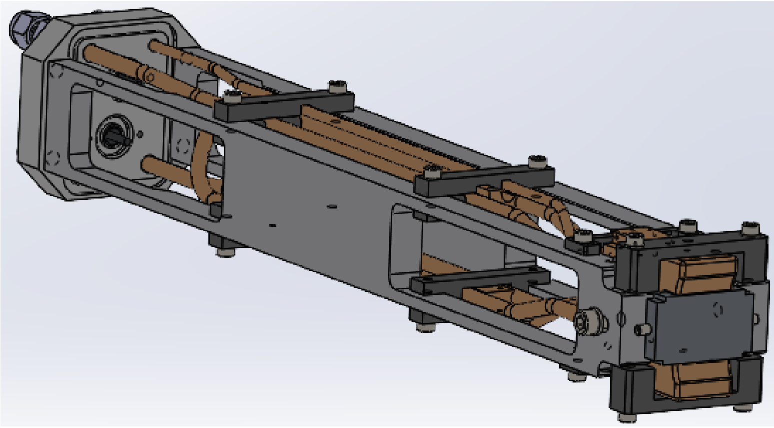


Figure 3.1: CAD model of IRISC ion source

Toolings for the bending of the water and hydrogen tubes and for the brazing were also designed. Including the 3D CAD models and the elaboration of 27 fabrication drawings. See on Figure 3.2 some examples of these CAD models.



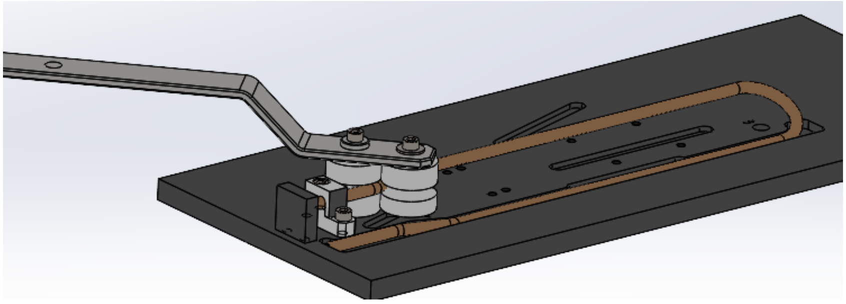


Figure 3.2: CAD model of brazing assembly (up) and water tubes shaping (down)

4 Fabrication

The fabrication of the IRISC ion source prototype involved the following activities.

4.1 Manufacturing of Parts by Machining

A total of 33 parts were manufactured by machining at different specialized suppliers. Most of them were made in copper, including the main bodies of the ion source, all the RF connections both at the main bodies end of the coaxial cable and at the flange end, the RF windows, the cap for the cooling circuit and the cathodes. The parts that were going to be part of the brazing were made in OFE copper, the rest of them in electrolytic copper. Cathodes in tantalum were also fabricated by wire cutting from a sheet. The flange was made of 316L stainless steel. Some other auxiliaries were made from aluminium. See on figure 4.1 some of the parts fabricated by machining.

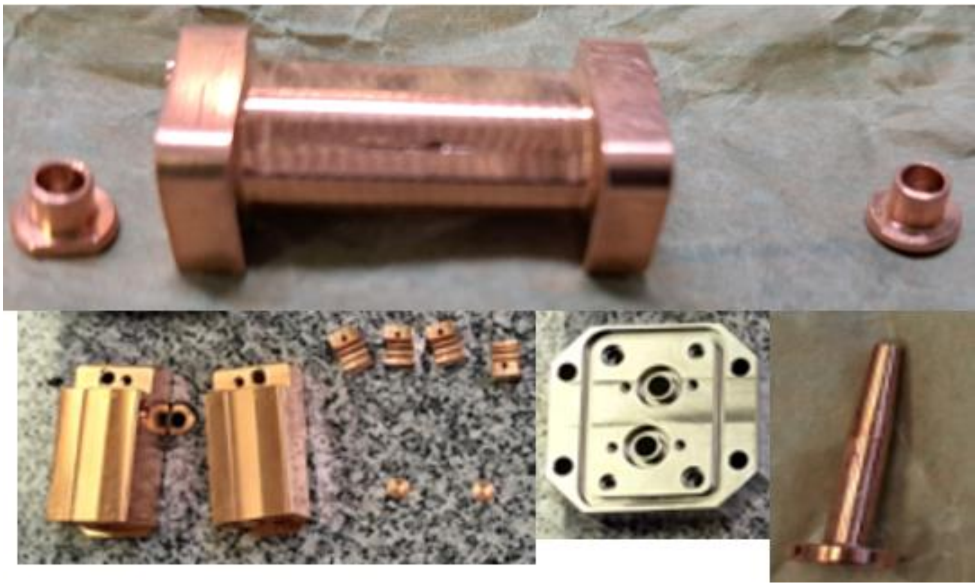


Figure 4.1: some parts manufactured by machining. Chimney and inserts (up), main bodies, cooling circuit caps and clamps for fixing the position of the tubes (bottom-left), flange (bottom-center) and RF window (bottom right)

The most critical parts with the strictest tolerances and roughness spec are the ones that are expected to have high electric or magnetic fields (from the ion source RF cavity or from the extraction cavity): the cathodes, RF window, internal walls of the main bodies, chimney and inserts. Also important are the tolerances in the dimensions determining the clearance of the unions by brazing or TIG welding.

4.2 Tubes Shaping

The shaping of the tubes is a critical step in the fabrication process because the water and hydrogen tubes are the only structural connection between the flange and the ion source main bodies. Although the finally assembled ion source has some flexibility, the proper shaping of these tubes is important for the correct position of the ion source inside the AMIT cyclotron or the IST (Ion Source Test) test bench.

This work was performed on the specifically designed tools. Each tube has a series of three dimensional bends (the final shape of the tubes is not contained on a plane) made by a system of sheaves. A specific plate for each tube has a system of drills and footprints for the tubes that allow their correct positioning for each bending step and to provide the correct amount of bend angle. Figure 4.2 shows one of the steps of the bending of one of the water tubes.

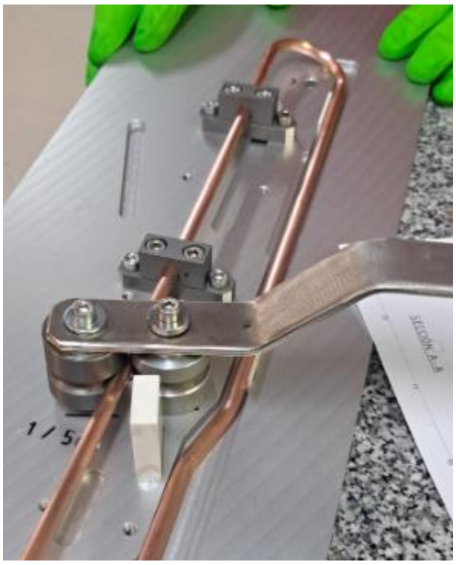


Figure 4.2: Bending step of a water-cooling tube

4.3 BRAZING

The two main bodies of the ion source, the cooling (copper) and hydrogen (stainless steel) tubes, the flange and the external water and hydrogen connectors were all joined together (a total of 16 vacuum tight joints) in a single brazing process. The brazing was performed in a vacuum furnace in a specialized supplier. The allow for the brazing was 1 mm diameter Palcusil 10 wire at all the unions.

The brazing is again a critical step in the fabrication process for the same reasons mentioned in section 4.2. The correct position of the ion source inside the AMIT cyclotron or the IST test bench is determined by a correct relative position of the ion source bodies and the flange after the brazing.

The brazing is performed with a specific tooling responsible for the correct positioning of all the elements. Dimensional checks to ensure the right positioning were performed after the assembly of the whole brazing structure with the tooling, both before and after the furnace brazing cycle.

See on Figure 4.3 images of some of the steps of the brazing process.

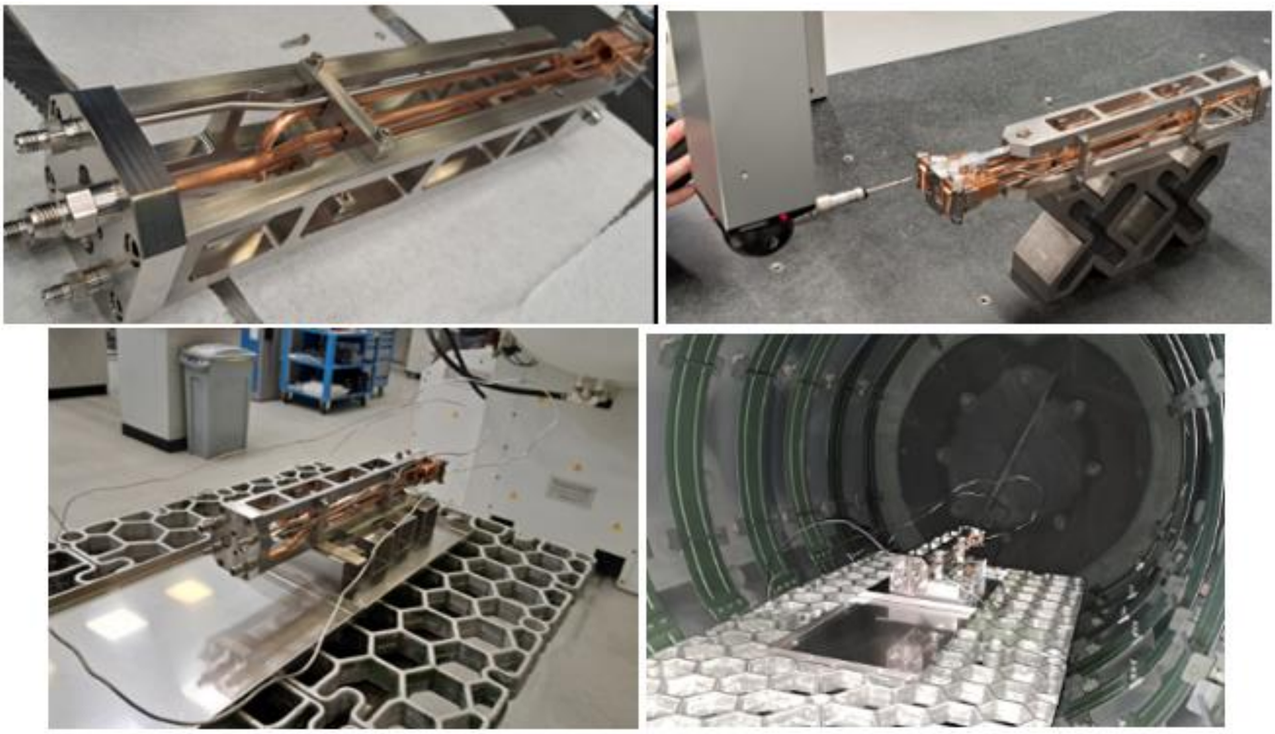


Figure 4.3: Some steps of the brazing process. Assembly of the brazing structure with the brazing tooling (up-left), dimensional check before the furnace cycle (up-right), temperature measurement instrumentation of the brazing assembly close to the furnace (bottom-left), brazing structure in position before closing the furnace door (bottom-right)

During the brazing cycle, one of the stainless steel tubes was not properly brazed because it slipped out of its position, due to a combination of too short dimension of the tube and a position of the tube too close to the flange that produced, after the initial deformations of the structure on the heating ramp of the cycle, that the tube fell out of its housing (see Figure 4.4).

Figure 4.4: Stainless steel tube displaces from its housing and not brazed

A vacuum test was performed for all the rest of the joints with good result.

After a study of the problem, the adopted solution for this problem consisted of enlarging the tube (its intermediate bendings allowed for this enlargement) and to repeat in a vacuum furnace the brazing just of that tube with a lower temperature brazing alloy.

This work was performed, and the tube was brazed on its housing, but a very small leakage was still found on a Helium leak test. The fact that the leakage was very small and that this union is not a critical vacuum one (it separates the vacuum of the chamber from the almost vacuum present inside the hydrogen tube) lead us to the decision of not performing any additional brazing step and to try to correct that small leakage by the application of an epoxy resin directly on it. After that operation the leakage disappeared (Helium leak level below $1x10^{-11}$ mbar.l/s, the same as the rest of the unions.

4.4 TIG Welding of the RF Feedthrough

The RF feedthrough responsible from transferring the RF power from the atmospheric pressure side to the vacuum side has an internal union with a ceramic insulator that would be damaged at the temperatures of the brazing with Palcusil 10 alloy. Its union with the flange has been performed by TIG welding at the tip of the part, according to the manufacturer specifications. See Figure 4.5.

Figure 4.5. RF feedthroughs TIG welded to ion source flange

4.5 Assembly

The assembly of the ion source involved the following steps:

- Manual cutting, shaping, and stripping of the semirigid coaxial cable that brings the RF power from the flange to the ion source body
- Assembly of the cathode with the RF window

- Connection of the window-cathode structure to the RF coaxial cable via the especial copper connector
- Assembly of the window-cathode-cable structure inside the ions source main body
- Connection of the opposite side of the RF cable to the feedthrough in the flange via the special copper connector
- Assembly of the chimney between the two ion source main bodies with the previous placing of both inserts at each end of the chimney.

Figure 4.6 shows images of some of these assembly steps.

Figure 4.6: Images of some of the assembly steps. Cathode – RF window – coaxial cable -copper connector assembly (up-left), insertion of that structure into the ion source main body (bottom-left), connection of the other side of the coaxial cable to the RF feedthrough at the flange side (bottom-center), assembly of the chimney (right)

The assembly was performed with only one important concern. The RF coaxial cable was a bit more rigid than expected, so its connection on the flange side after being connected to the main bodies side was extremely difficult. The cable had to be forced, temporarily overpassing the minimum bending radius recommended by the manufacturer, and in the final position the cable is forced causing excessive tension that tends to produce misalignments and may produce an inefficient power transfer.

Taking this into account, for a second assembly an intermediate connection for eaasier assembling on a perpendicular direction to the cable was designed, calculated and fabricated. With this connection, the cable is cut in two parts each of them being easily connected to the flange and the main body sides. This intermediate connector is designed for being able to connect both cables just by a small movement perpendicular to the cables, avoiding any excessive bending or tensions. These intermediate connections were simulated and optimized to minimize the power loss and the VSWR. See Figure 4.7.

Figure 4.7: Intermediate connections mounted at each of the coaxial cable lines of the ion source

5 Testing Facility

The Ion Sources Test bench (IST) is a facility in CIEMAT dedicated to the test of compact ion sources. Its original characteristics were as follows:

- 0.8 Tesla Dipole
- Vacuum chamber with two diffusion pumps
- Precision hydrogen flow measurement and regulation system capable of providing a flow between 0 and 10 sccm.
- DC high voltage extraction system capable of providing up to 10 kV of extraction voltage. The ion source is at ground potential. The puller is at high potential and is being kept isolated from the rest of the vacuum chamber. Behind the puller a Faraday box isolates all the diagnostic devices, which are at the same voltage as the puller.
- A security fence for protecting from the high voltage, inside of which the rack including all the electronics for the diagnostics is kept at high voltage. The connection between the high voltage rack and the grounded one is made through optical fiber cable.

The operation of this facility has had some problems regarding the frequent production of arcs, which affect the electronics and damages the components.

An upgrade of the facility has been done. The most significant change is that a new vacuum chamber has been developed including a RF extraction system. It consists of an approximately 60 MHz quarter wave resonator capable of producing a voltage of up to 10 kV. The ion source is located inside of the stem. The stem is composed of four copper plates located around the ion source, the chimney of which is exposed at the extreme of the stem. The ion source is therefore the one that will be at high voltage, while the puller makes contact and is at the same voltage with the walls of the cavity around it. This allow for all the diagnostics located behind the puller to be at ground voltage and avoids the need for a Faraday box, an isolated high voltage rack and security measures in the facility.

The design of this RF cavity has been made with the objective of providing the desired extraction voltage with a cavity as simple and cheap as possible and with a power loss as low as possible, taking advantage of the fact that the extraction area, in which we need a high voltage and electric field has small dimensions (in the order of the ion source chimney) and therefore, a reduced capacitance. A complete RF and thermal simulation has been performed for the extraction cavity, showing a resonant frequency of 61.38 MHz, Q factor of 6120, and total power loss of 151.2 W for 10 kV extraction voltage. See Figure 5.1.

To keep things simpler, no tuning system has been considered. There is no need to work at a certain frequency, so the frequency provided by the RF generator will adapt to whatever resonant frequency the cavity is having at any moment. The tuning system will act on the generator frequency.

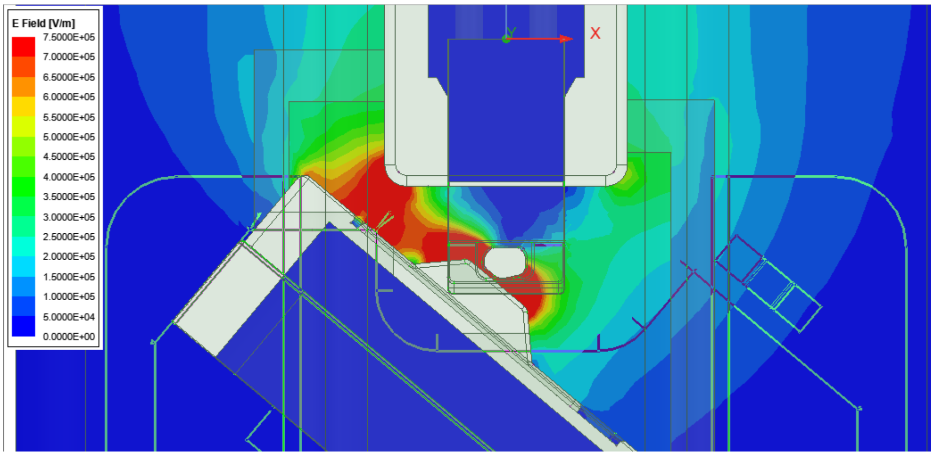


Figure 5.1: Electric field at the central zone of the extraction cavity

No cooling system other that the natural convection on the external walls of the cavity and the own cooling system of the ion source through which part of the power loss in the extraction cavity is needed. The simulations show that this approach is reasonable, giving a maximum temperature of 100 ºC on some stainless-steel parts of the cavity on a very conservative calculation, which we consider enough. Anyway, we keep the option of applying an external air forced cooling system on the exterior of the vacuum chamber in case the temperatures can affect the performance of the extraction cavity. See Figure 5.2.

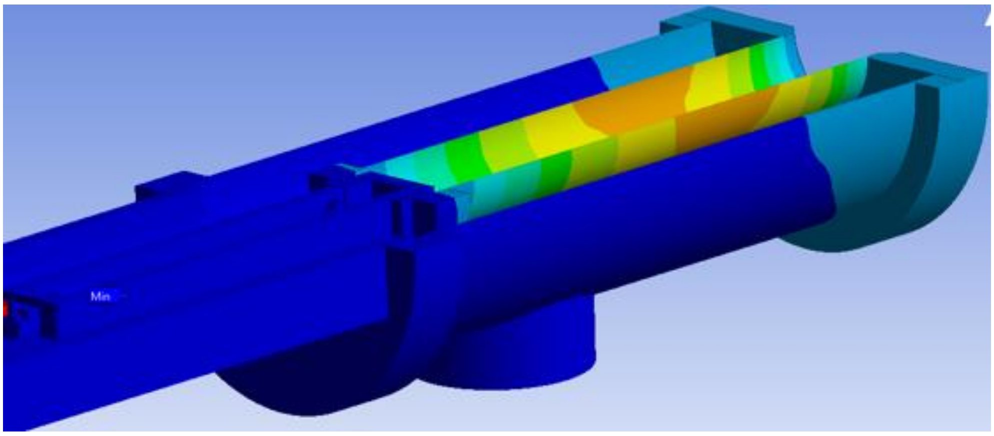


Figure 5.2: Temperature distribution at the extraction cavity working at 10 kV extraction voltage. Maximum temperature is in the order of 95ºC

The vacuum chamber is fabricated in 316L stainless steel with an internal electrodeposited copper layer. The internal parts of the cavity (stem and puller) are made of electrolytic copper. See on Figures 5.3, 5.4 and 5.5 some details of the construction of the vacuum chamber and the RF cavity.

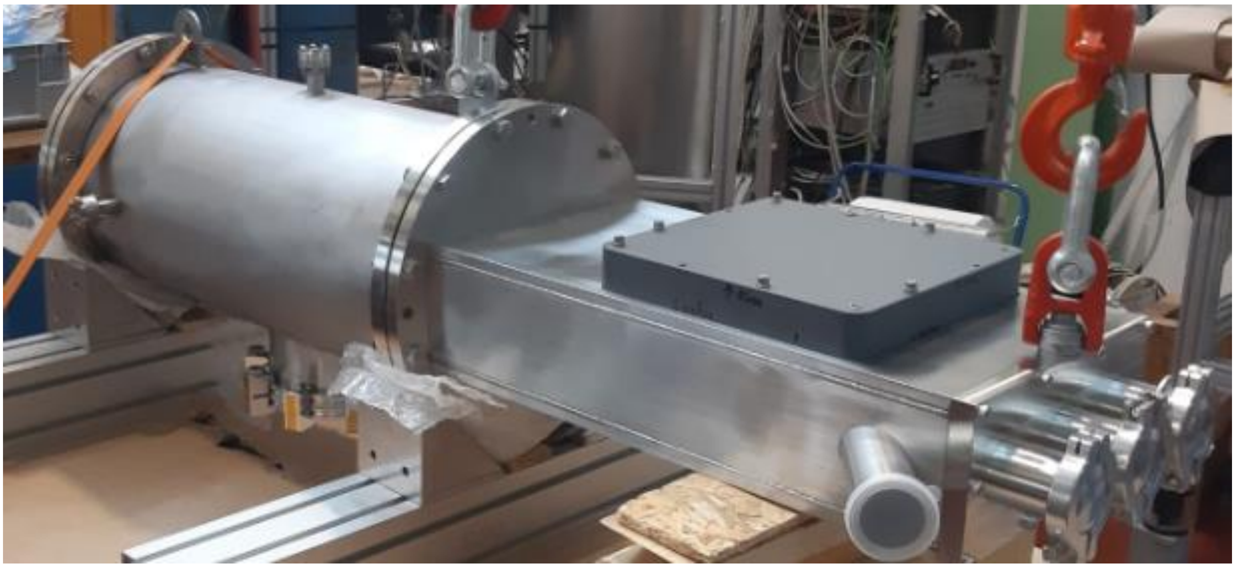


Figure 5.3: New vacuum chamber for the ion source test facility

Figure 5.4: central zone of the extraction cavity showing the stem and the puller (with no ion source)

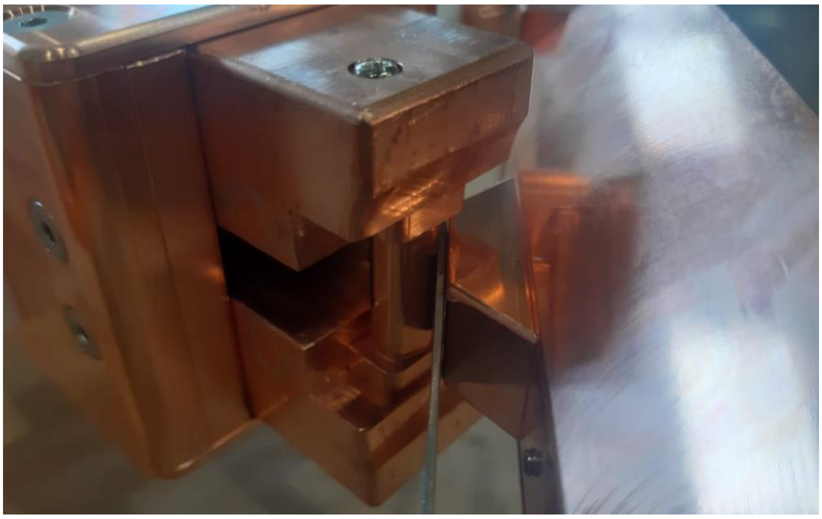


Figure 5.5. Checking with a gauge the distance between the ion source wall and the puller

Other new features of the IST facility are:

- New vacuum system based on a primary pump and a single turbopump.
- New control system based on a PLC
- New RF control systems based on cabled components, a much simpler and cheaper solution than developing or acquiring an FPGA system or similar and enough for the purposes of this facility. These RF control systems were developed both for the ion source 2.45 GHz RF and for the extraction cavity 60 MHz RF.
- New software interface integrating all the systems of the facility in LabVIEW.
- A customary developed data acquisition and graphics representation system.
- A spectrometer for the analysis of the visible light emitted by the plasma, with an optical fiber line for bringing the light from the ion source aperture to the equipment located outside of the vacuum chamber. By analysing the spectrum, plasma parameters like electron density, electron temperature, atomic to molecular population ration and ionic to neutral population ration can be estimated.

6 Tests

6.1 Ion Source Low Power Test

The low power test of the ion source consisted in the analysis of the frequency response of the RF cavities of the ion source, measured with a Vector Network Analyzer device. The cavities have only one RF port (power input), so only the S11 parameter was measured.

The measurements were performed by combining the two types of cathodes fabricated (copper and tantalum) and the two sizes of RF window (coupler) fabricated. Figure 6.1 shows the configuration for the measurement, Figure 6.2 shows a detailed view of both cathodes assembled into the internal body of the ion source, and Figure 6.3 show the frequency response of the cavity with three different configurations of cathode and RF window. The fourth possible configuration (tantalum cathode with small coupler) was not tested because it would be obvious that it would give a non-valid coupling factor with too much reflected wave.

Figure 6.1. Ion source low power test configuration

Figure 6.2. Copper and tantalum electrodes assembled on the ion source internal body

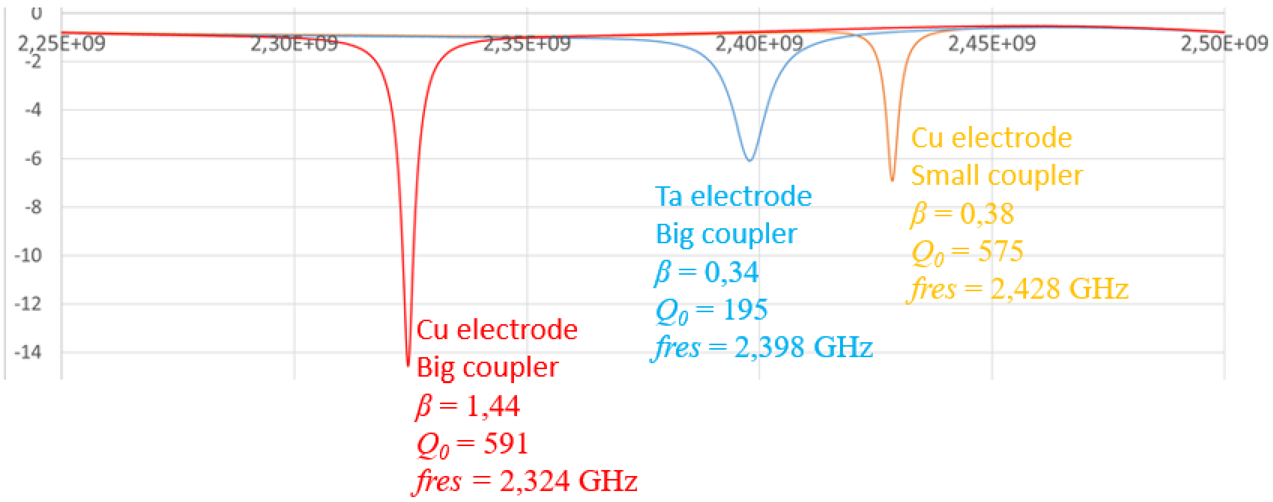


Figure 6.3. Frequency response (S11 parameter) of the ion source cavity with the different configurations

As shown in Figure 6.3, with the copper electrode and the big coupler the coupling factor is closer to 1 and the reflected power at resonance is lower. It is evident that it would also be the case with the tantalum electrode although the tantalum electrode has not been tested with the small coupler.

6.2 Ion Source Power RF Tests

Both cavities of the ion source were tested up to 100 W power with copper cathodes. Both can stay at that condition a steady state with a reflected power in the order of 30%. This corresponds to an estimated voltage in the cavities of around 3 kV, which is the nominal design voltage.

6.3 Hydrogen System Test

The reliability and repetitivity of the hydrogen system was tested. The precision hydrogen flow measurement and regulation system was connected to a hydrogen tank through two pressure reductors in series. The whole regulation range (from 0 to 10 sccm) was tested, The regulation of the valve is precise, fast and reliable. The vacuum pressure stabilises on order of magnitude higher when 10 sccm (maximum flow provided by the system) compared to no flow of hydrogen.

6.4 First Plasma Production

An initial check of the capacity for plasma production of the ion source was done with copper cathodes. The dipole was working at nomminal magnetic field (0.8 Tesla). No instrumentation for the plasma characterization was present. The presence of plasma was checked visually through a window in one ofc the ports. The chymney used for this test was the instrumented one, with a circular drill instead of the slit for the extraction of the beam, with the same section. See Figure 6.4.

Different hydrogen flows were used for this test, with almost the same result. At a constant hydrogen flow, the RF power of both cavities simultaneously is ramped up until the plasma starts, which happens at about 70 W incident power, 50% reflected power, corresponding to an approximate voltage of about 2 kV.

Once the plasma has started, the RF power can be reduced down to about 2W, corresponding to a voltage in the order of 400 V.

When the RF power is present, the hydrogen flow can be reduced, or even eliminated and the plasma is not stopped for at least 10 minutes. Even when the hydrogen flow is set to 0, and the RF is turned off, thus stopping the plasma, if the RF is turned on again up to 70 W without any new hydrogen gas flow, the plasma starts again just with the residual gas present in the ion source. About at least one hour of vacuum pumping is necessary to eliminate enough residual gas in the ion source that the plasma cannot start again.

When the plasma starts, the RF reflected power goes down immediately from about 50% to about 10 %. Further work is necessary to analyze the reasons for this effect.

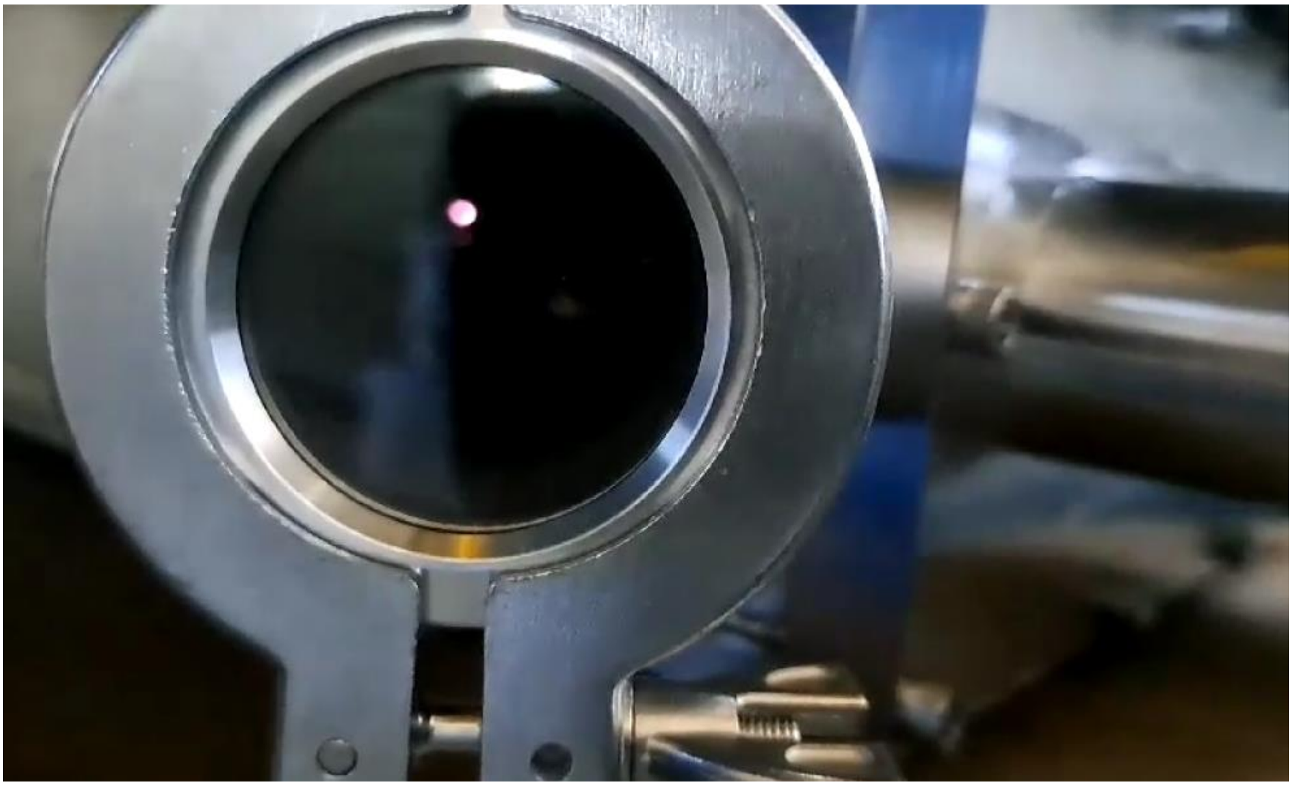


Figure 6.4: plasma produced in the ion source directly seen from outside of the vacuum chamber

6.5 Extraction Cavity Conditioning

A preliminary test of the extraction cavity at high power has also been done. Not much conditioning time has been accumulated at this point (about 5 hours). A lot of non-linear effects in the frequency response of the cavity probably due to the appearance of dark currents make it difficult to properly tune the cavity over an incident power of about 2-3 W. Also some arcs have been produced in the cavity. The maximum power injected in the cavity has been about 16 W (incident power) with 40% reflected power, corresponding to an approximate extraction voltage of about 3 kV. Figure 6.5 shows a frequency response curve of the cavity with 50 mW injected power, one of the highest power levels where the resonance of the cavity can be clearly detected, with a reflected power below 10%, corresponding to a voltage in the cavity of about 160 V.

More working time is necessary for conditioning the cavity for reaching the nominal extraction voltage of 10 kV.

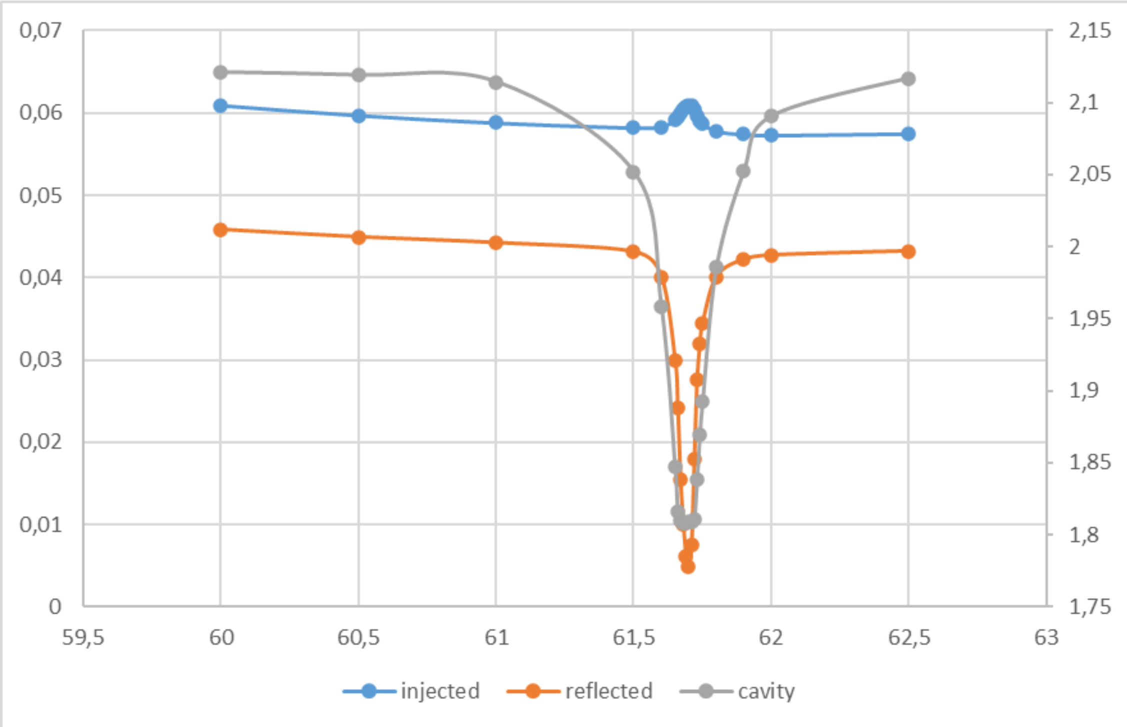


Figure 6.5: Frequency response of the cavity with an incident power of 50 mW. The cavity voltage signal is not calibrated, just the voltage seen on the power detector (which happens to have an inverse relationship with the cavity voltage) is shown. The reason for the small bump in the injected power at the resonance is still unknown. It can be due to some sensibility of the RF generator to the reflected power or to the frequency. A directivity error of the directional coupler can also have some influence

7 Annexes

7.1 Annex I. Market research report

Market research: Ion Sources

7.1.1. Introduction

An ion source is a device which is capable of creating atomic and molecular ions, this is, atoms and molecules whose electrical charge is not neutral. Nowadays there is great variety of methods to produce these ions, as well as industrial applications where they are crucial.

Because of the fact that ions are electrically charged they are affected by external electric and magnetic fields. By the force that appears when such fields are applied it is possible to create ion beams (a constant flow of ions) in order increase their speed in particle accelerators or force impacts with other elements in mass spectrometry applications. The are 4 common elements to ion sources:

- Ionization chamber: an empty cavity in which the process of ionization takes place, and where the ions are deviated towards the extraction system.
- Material: Whatever is used to feed the ion production, typically a gas (or a compound gas) which is heated under controlled conditions.
- Energy source: The ionization process requires energy; therefore, it must be supplied trough an external element (typically electric power).
- Extraction system: A hole in the ionization chamber from which the ion beam is extracted. In order to extract the ions an electric field is required.

The ion source market is strongly associated with technological development, which is why it has experienced great growth in recent years and is expected to continue growing in the future. In the context of this technological development is where the Cyclomed ion source is found, which will be detailed later in this document, together with its advantages over ion sources already existing on the market.

7.1.2. Classification

The main types of ion sources are briefly discussed in this chapter. As such, there is no precise and consensual classification of the types of ion sources, which is why the most relevant types within the industry are explained, but there are others.

7.1.2.1. ELECTRON IMPACT

These ion sources contain an anode and a cathode. Electrons are generated at the cathode, by the thermionic effect, and they are accelerated through a potential difference between cathode and anode. Between these two elements, there is a chamber called the "ionization region", where there are electrically neutral atoms. Electrons collide with these neutral atoms, turning them into ions. There is a small extraction slot inside the chamber through which the ion beam is extracted. The following figure shows the main parts of an electron impact ion source [1] :

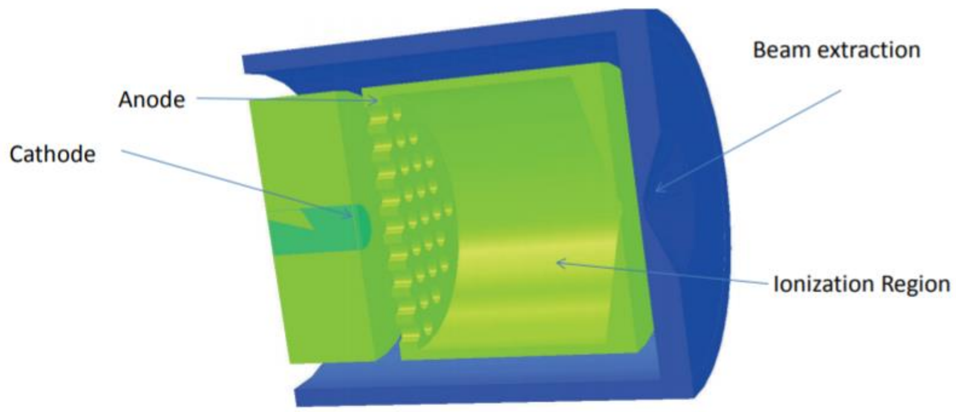


Figure 1: Electron impact source scheme

7.1.2.2. Plasma discharge sources

In these sources the principle of operation is the following: the temperature of a gas inside a chamber is increased, until a plasma is formed, from which the ions are subsequently extracted. Plasma is a state of matter that is reached when a gas rises to a high temperature [2]. In this state the electrons of the atoms are "released" from the nucleus, so the plasma becomes a good conductor. Unlike the electron impact sources, where the thermionic effect is the one that governs the impacts between the electrons and the neutral atoms of a gas, in plasma sources it is the ions and electrons themselves created from the gas that drive the current between anode and cathode.

Once the plasma is formed, and due to its properties, where the electrons are "separated", it is easy to extract a beam of ions, through a mechanism similar to that of electron impact sources.

Within plasma discharge ion sources, the following subtypes are worth being highlighted: plasmatron, duoplasmatron, magnetron and PIG (Penning Ion Gauge). The following image sums up the physical configuration of these sources:

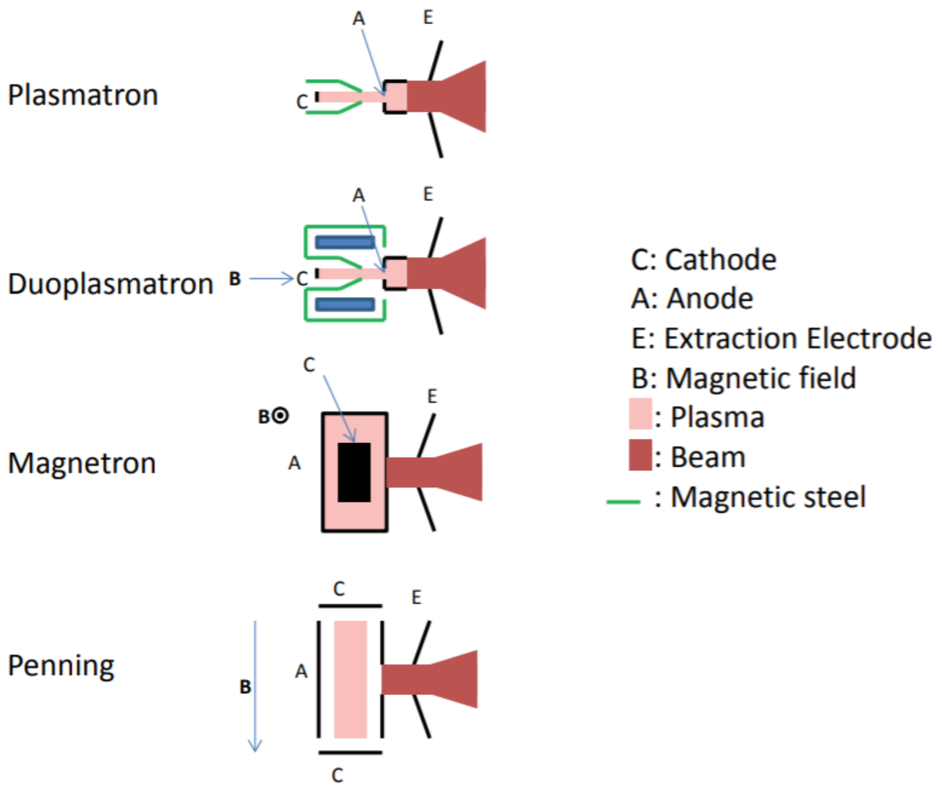


Figure 2: Types of plasma discharge sources

All these sources share the characteristic that it is easy to extract almost any type of ion beam from them, with a wide range of intensities and pulse structures; however, all of them have a limited lifecycle due to the sputtering of the cathode [3], which is constantly being bombarded by electrons. The rate at which these impacts occur depends on the cathode material, the type of ion and the impact energy.

This means that it is necessary to periodically change the cathodes from such sources. This way, whomever is in charge of performing maintenance is exposed to possible ionizing radiations.

7.1.2.3. RF discharge sources

RF sources come from the idea of a source in which the electric field is created externally, instead of through the potential difference of anode and cathode. In this case, the movement of the electrons is caused by an electric field, which can be generated inductively or capacitively. This last way of generating the field has the disadvantage that the field lines end at the capacitor's own terminals, making them like that of the cathodes and anodes of the plasma discharge sources [4].

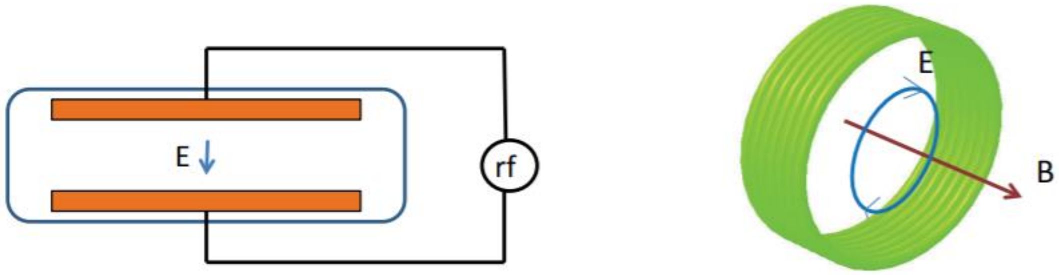


Figure 3: Types of RF ion sources

Typically, the frequencies used in these systems do not exceed a few tens of MHz, which is why the plasma resonance frequency of the ionizing gas is not usually reached. Therefore, it can be concluded that its behavior is similar to that of a discharge source with cathode and anode, but with a different electron acceleration mechanism. As a cathode or anode may not exposed to sputtering, it potentially requires less maintenance.

7.1.2.4. ECRIS

The acronym comes from Electron Cyclotron Resonance Ion Source. As it is stated in the name, in these sources the resonant effect of the plasma is used to create collisions between the electrons and the neutral gas that is to be ionized.

Charged particles within a magnetic field rotate with a frequency that depends on the intensity of the field. In ECRIS-type sources, a series of microwaves whose frequency is equal to the rotation frequency of the charged particles (electrons) are injected, causing a resonance effect [5]. This effect causes a very efficient heating of the electrons, which is translated into greater ionization of the plasma, making the process stable.

As in the RF source, maintenance does not imply such a significant problem, as it is in the case of the plasma discharge ion sources, due to cathode and anode sputtering.

7.1.2.5. Laser ion sources

A laser consists in a monochromatic beam of high energy photons, and it can be used in two different ways in ion sources.

The first is laser ionization, in which a beam directly ionizes the atoms. These sources are based on the idea of a beam of photons of energy greater than the ionization potential of the material (energy necessary to ionize an atom) to be ionized. However, the wavelength required to ionize materials with lower ionization potential is already too small for commercially available lasers. For this reason, photon beams of different energies are chosen, in which some photons excite the electrons to higher energy states (reducing their ionization potential), and subsequently other low-energy photons finally ionize the atom. Using different energy levels allows you to select the type of ions you want to produce.

The second possible configuration of laser ion sources is that of laser plasma sources. In this configuration an intense laser radiation is used to produce a plasma, from which an ion beam is extracted. The following image provides a graphical representation of this process [6]:

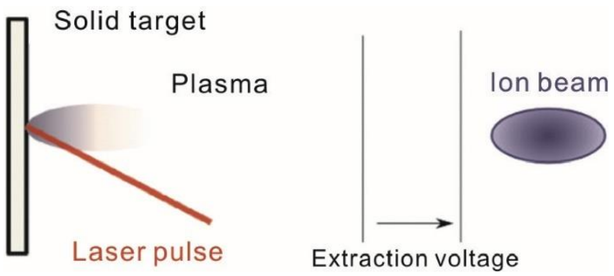


Figure 4: Laser ion source (Plasma type)

7.1.2.6. Surface ion sources

In any material, the electrons that are located in the different energy levels can be released, providing them with a certain amount of energy, called the work function. This effect can be used to force a thermionic effect on a given material, creating surface ions, and subsequently extracting these ions. Within the atoms extracted from the surface of the material only a proportion of these will be ions, the exact proportion depends on the temperature, the work function and the ionization potential.

7.1.2.7. Charge Exchange ion sources

The electronic affinity of an element is the change in energy of an atom of this element when an additional electron is added to it. In the case of hydrogen, it is a positive magnitude, which means that it is necessary to apply energy to "pull" an electron, and this means that negative hydrogen ions can exist. In a charge exchange ion source, the exchange of electrons between a positively charged particle and neutral atoms is used. Typically, a neutral gas is bombarded with positive hydrogen ions (protons) with a certain energy level that makes them to easily perceive electrons, so that they accept two electrons from the "donor" gas, becoming negative ions. Thus, for this type of ion sources another source of positive ions is necessary.

Positive ions are easier to generate, but in many applications, it is more convenient to work with negative ions. For example, in particle accelerators, negative ions are accelerated until they reach a carbon sheet that extracts their electrons, causing them to change their electrical charge (from negative to positive) and therefore their trajectory, which is very useful for an extraction mechanism.

7.1.2.8. Summary

After having presented the most relevant types of ion sources it is important to summarize the main differences and similarities between those types:

ION SOURCE TYPE	ADVANTAGES	DISADVANTAGES
Electron impact	Simple and sensitive	Molecules have to be volatile
Plasma discharge	Wide variety of beams and ions can be created	Cathode and anode sputtering
RF	No cathode sputtering	Complex system required
ECRIS	No cathode sputtering and high efficiency	Complex system required
Laser	High level of isotope selectivity	Expensive
Surface	Very simple mechanism	Low ionization energy required
Charge exchange	Can produced polarized ions. High efficiency.	Requires a positive ion source

Table 1: Ion source types comparison

7.1.3. Applications

In the same way that the main types of ion sources have been explained in the past chapter, in this one, the most typical applications are briefly explained, which do not include all the applications of ion sources, as they are a technological element under development, where new applications are found as technology grows.

7.1.3.1. PARTICLE ACCELERATORS

Particle accelerators are one of the most common applications for ion sources. Independently from the type of particle accelerator, the acceleration mechanism is always the same: a charged particle, this is, an ion, is accelerated in a path guided by electric and magnetic fields. Therefore, the ion source provides the charged particles that are to be accelerated.

There are many types of particle accelerators, and many applications as well, both in the industry and for research applications. The following figure provides a brief summary of the size of the most relevant applications:

Figure 5: Global particle accelerator share between applications [7]

The classification of particle accelerators can be made through their physical configuration [8]. Depending on the electromagnetic fields used, accelerators can be classified into electrostatic (static electric fields) and electrodynamic (time varying electric and magnetic fields). The most relevant type of electrostatic accelerator is the Van de Graaff type.

Within electrodynamic accelerators the two main types are the linear ones and the cyclic ones. Linear accelerators provide a straight-line path for the ions, while cyclic ones offer a circular pattern. While the acceleration of ions in the linear types is limited, in the cyclic ones the fact that ions can travel many times through the same circuit allows for higher energies.

Within cyclic accelerators the two main types found in the industry are cyclotrons and synchrotrons. The main difference between them is that in the cyclotron configuration the particle follows a circular path of increasing radius, while synchrotrons present a constant radius circumference. The following figure provides a basic scheme for each one of those:

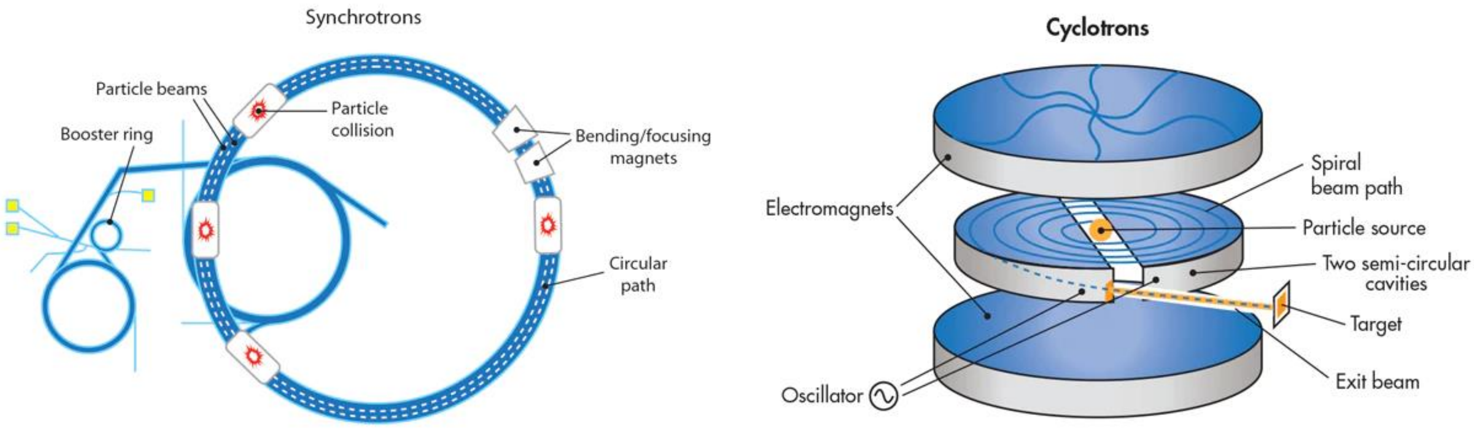


Figure 6: Synchrotron / cyclotron basic configuration

Apart from the physical configuration of the particle accelerator, one of the most important parameters in such systems in the energy reached by the ions once they are fully accelerated, measured in electronvolts (eV). Depending on this final energy, accelerators will be suited for certain applications.

The best suited type of accelerator for Cyclomed Ion Source is the cyclotron. We can distinguish between three main systems that make up the cyclotron: 1) the ion source: which takes care of particle production; 2) the radiofrequency system: which provides the alternating electric field; and 3) the magnetic system: composed by magnets, whose tasks is to produce the guiding magnetic field. These systems can bee seen in Figure 6.

The cyclotron is formed by two semicircular plates, called “D”, which are set with their diametral borders adjacent to each other, as we can see in Figure 1. In order to accelerate particles a high frequency oscillating electric field is applied to the plates, in the region between “D”s.

Ions are accelerated during a semicycle by the electric fields to the interior of one of the electrodes (D) making a circular trajectory until reaching its intermediate zone, in which the electric field is adjusted so its spinning direction is changed and the ions keep accelerating, receiving a second increase in their velocity when reaching the interior part of the other “D”.

As for the applications of particle accelerators, the two most relevant ones have been mentioned: industrial and medical.

Industrial applications encompass several fields [9], such as:

- Ion implantation: Semiconductors are one of the key components of almost all electrical devices from mobile phones to desktop computers. They are materials that conduct a small amount of electricity, more than an insulator but less than a conductor, hence the name. Semiconductors are usually made from silicon - sometimes germanium - that has been doped. Doping is the process of adding impurities to the silicon so that an electric current flows through the material (silicon crystal is an insulator). The doping of silicon is done by a process known as ion implantation. In this process, a beam of ions is fired at a target material. The ions then penetrate, and come to rest within the material at a penetration depth related to the energy of the beam. The development of ion implantation technology leads to better and cheaper semiconductor production, which in turn drives down the cost of electronics and improves the quality of the product.

- Electron Beam material processing: As the name suggests, electron beam welding (EBW) uses a focused beam of electrons to fuse together two materials. As the beam collides with the metal, the kinetic energy of the electrons is transferred into heat. The heat from the collisions causes the metal to melt and flow together, which joins the two pieces when the molten metal cools. EBW can weld very thin pieces of incompatible alloys with minimal thermal deformations resulting from the process.

- Treating waste: Beams of electrons fired from small particle accelerators are used in factories that produce medical apparatus to sterilize them. The beam of electrons kills any microbes without damaging the equipment or the packaging, an advantage this method holds over other sterilization techniques.

- Food preservation: The same process is used for food preservation. However for irradiation of food items, it is essential to select a dose high enough to kill or prevent the bacteria or insect from reproducing, and low enough that it does not damage the food. Many food products are treated using an electron beam: fruit and vegetables, cereals, spices, fish, fresh meats…

- Oil and Gas Exploration: When searching for new oil deposits, exploratory boreholes are drilled into the ground and the geological structure surrounding the borehole is recorded. One of the techniques used to carry out such investigations is called 'Neutron Logging', where by a small portable particle accelerator known as a 'Portable Neutron Generator' is lowered into the borehole along with gamma ray detectors. As the neutrons from the accelerator pass through the materials surrounding the borehole they interact with the nuclei in the different materials and high energy gamma rays are emitted. The gamma rays are picked up by the gamma ray detectors and the data is transmitted to a computer. The data is then used to predict the likelihood of finding oil or gas.

Medical applications of accelerators can be summarized within the following two groups:

- Treating cancer: One of the most important of all applications of particle accelerators is their application in the treatment of cancer. Cancer takes on many forms, so the treatment for cancer must also take on many forms. The main types of cancer treatment are: surgery, where the cancerous tissue is surgically removed; chemotherapy, where powerful cancer-killing medicine is given to the patient and radiotherapy, where the cancer is destroyed by energy deposited by radiation. Accelerator based treatments fall into the category of radiation therapy. Presently about 50% of all patients with cancer will undergo radiation therapy often in conjunction with other treatments such as chemotherapy or surgery. The most common form of radiation therapy is external beam radiotherapy where a beam of radiation is fired into the body by a particle accelerator.

  The advantage of proton and ion-beam therapy (both produced with particle accelerators) over current X-ray radiotherapy is that the particles do not penetrate the whole body; they are fired into the body with a certain energy which dictates the range of the particles. The range is the depth that the protons or ions can penetrate into the body. Once protons or ions reach this depth they stop, whereas X-ray radiation passes through the whole body, thus also damaging cells on the way in and on the way out. Using protons or ions, this means that, for a certain dose in the tumor, the patient is exposed to less radiation in regions outside the tumor and therefore less healthy tissue is damaged in the treatment. The following image provides a clear visualization of the penetration of different types of radiotherapy:

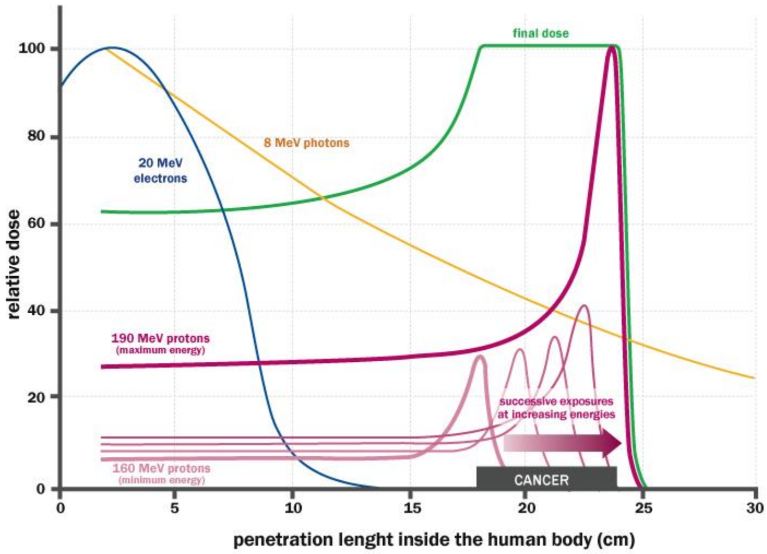


Figure 7: Levels of penetration in radiotherapy

- Medical imaging: The most important techniques for medical imaging that involve particle accelerators are PET and pCT.

  Positron Emission Tomography (PET) is a medical imaging technique which produces a detailed 3D image. A radioactive isotope is introduced to the body. The isotope undergoes radioactive decay within the body which emits a positron. As this particle travels through the body, it interacts with other particles in the body and slows down to the point where it can annihilate with an electron producing a pair of gamma photons. These photons are then picked up by a detector which will send the data to a computer for the production of an image of the photon origins.

  Particle physicists and medical researchers are working together to develop a new medical imaging technique called a proton computerised tomography (pCT) scan, which is like a conventional computerised tomography (CT) scan but uses protons rather than X-rays. This new technique will reduce the patient's exposure to harmful radiation whilst producing more accurate 3D images than those produced by current CT scans. A pCT scan also has great potential in improving the effectiveness of proton beam therapy which could improve proton therapy, and reduce side effects related to still existing range uncertainties of the proton beam.

7.1.3.2. MASS SPECTROMETRY

Mass spectrometry is a technique used to measure the relation between mass and charge of ions. The result of a mass spectrometry process is typically a mass spectrum, which plots the intensity as a function of the mass-to-charge ratio [10]. This spectrum is used to determine the masses of particles and molecules that make up a sample, which can either be pure or a complex material.

The following image illustrates the working mechanism of a MS system:

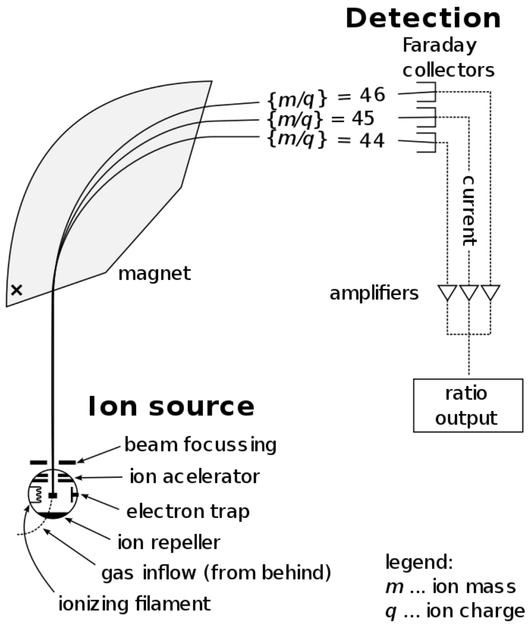


Figure 8: Mass spectrometry general scheme

The ion source takes the sample and ionizes its atoms, typically with an electron beam. When the ions are formed, they are guided to a magnetic field, which provides different curvatures depending on the charge of the ions, therefore changing the trajectories as a function of mass-to-charge ratio of the ions. At the end of the trajectory there are detectors, which provide the information required for the spectrometry.

7.1.3.3. MATERIAL SURFACE TREATMENT

There are some applications within the industry regarding the treatments of materials, especially surface treatments. Some examples are surface cleaning, thin film deposition (films of nanometers of length), and treatment for polymers, such as surface roughening, which can improve its adhesion and biocompatibility properties.

7.1.4. Ion source market

The scope of this chapter is to provide an approximation of the size and characteristics of the ion source market on a global perspective. The approach will start taking into account the size of the market of all the applications and focusing on the corresponding share of the ion source components within those markets. The units in which market sizes are measured are millions of USD, or MUSD.

7.1.4.1. Overall market

As we mentioned in previous chapters the most important applications of ion sources are particle accelerators, mass spectrometers and material treatments. We will derive the market size for these industries.

As we can see in Fig. 5 (P. 37), particle accelerators worldwide are used for medical purposes and industrial applications, with the first one accounting for 1/3 of the units and the other one for the remaining 2/3 (we will assume the research purposes of particle accelerators are negligible compared to medical and industrial). The global particle therapy market is projected to reach USD 1,349 million by 2023 from USD 865 million in 2018, at a CAGR of 9.3% [11]. Particle therapy involves the use of either cyclotrons or synchrotrons (or variations of them, like the synchrocyclotron). This market growth is explained by the aging population and, therefore, an increasing demand of treatments such as PET radiopharmaceuticals [12], which are produced with particle accelerators.

The mass spectrometry market size is expected to grow from an estimated USD 4.1 billion in 2020 to USD 5.6 billion by 2025, at a CAGR of 6.5% [13].

The material treatment market size requires a more complex analysis, because of the fact that there are many applications and varieties of processes. This makes it hard to find an estimation of the corresponding market share of ion sources within these applications. We will assume that the ion source market for material treatments is negligible compared to that of particle accelerators and mass spectrometry.

The following table provides a summary of market sizes (in MUSD), estimations and the share of ion sources within these markets:

Application	*Market size (2021)*	*Market size (2025)*	*Ion sources*
Particle accelerators (medical)	1129	1611	2%
Particle accelerators (industry)	2258	3222	2%
Mass spectrometry	4360	5600	5%

Table 2: Ion source applications market size

The total particle accelerator market size is estimated through the size of the particle therapy market and assuming this represents 1/3 of the total market size (industrial + medical). The estimations on the share of ion sources within the particle accelerator market come from the cost associated with the ion source with respect to the cost a commercial particle accelerator. The specific numbers come from the AMIT cyclotron of Cyclomed, in which the ion source cost (both materials and production) represents around 2% of total cost. Price of mass spectrometry systems vary a lot depending on the manufacturer and application, but an estimate of 30.000 USD can serve for the purpose of this market study. As ion sources are less demanding for these applications than those of particle accelerators the overall cost is lower, but so is the total system cost, so an estimate of 5% is given for the share of ion sources within the mass spectrometry market. Taking all this information into account yields the following total market size for ion sources (in MUSD):

Market	*Market size (2021)*	*Market size (2025)*
Ion sources	285	376

Table 3: Ion source market size

7.1.4.2. Cyclotron market

Because the ion source of Cyclomed is focused on cyclotrons, particularly for medical applications, we will develop a further study in this particular market. Despite the fact that the market for cyclotrons for medical use is very specific, there are studies that estimate its size at around 145 million euros with an annual growth forecast of 10.9% [14], reaching 260 million euros in 2025. The following table offers the market size of the different types of cyclotrons within this application:

Cyclotron type	*Energy (MeV)*	*Units*	*Use*
Low-energy cyclotron	< 20	1100~1400	Hospitals, Universities and Production Plants
Medium-energy cyclotron	20 – 35	100	Research centers and regional production plants
High-energy cyclotron	> 35	50	Research and proton therapy centers

Table 4: Cyclotrons for medical applications market

Taking the proportion of the cost corresponding to the ion source system within the whole accelerator, we can estimate the ion source market size for cyclotrons for medical purposes reaches up 4 MUSD in 2021 and is estimated to grow to 5,2 MUSD in 2025.

7.1.5. State of the art

In this chapter we will overview the state of the art regarding ion sources, focusing on internal ion sources for cyclotrons. We will first present a brief summary of the state of the art and then locate the ion source from cyclomed within this context and describe its most relevant features.

7.1.5.1. State of the art analysis

The different types of ion sources have been mentioned in chapter 2, but when the application for the source is a particle accelerator there is another classification, as for where is the source located within the acceleration system. Ion sources can either be internal, when the source is part of the acceleration mechanism itself, or external, where ions are generated elsewhere and then transported to the acceleration system. We will focus in the state of art of internal ion sources, as Cyclomeds Ion Source can be classified as such.

Internal sources have multiple design constraints because of the magnetic field present in the acceleration system and limited space for its components, but they don´t require a complex and expensive system for carrying the ions from the source, with their corresponding efficiency loss.

The only configuration available nowadays for such type of ion source is the one with 2 cathodes, either hot or cold ones. Internal ion sources present a very easy extraction system, as they are located in the cyclotron itself, with the downside that there is a poor vacuum due to gas injection into the cyclotron chamber. On the other hand, external ion sources generate the ions outside the cyclotron. There are multiple configurations, but the injection system is usually very complex. A good quality vacuum can be easily generated.

The only internal ion sources for cyclotrons that have been used until now are of the Penning type (PIG) [i]. As we have mentioned in chapter 2, PIG sources are simple to use, but their cathodes are exposed to sputtering and therefore require extra maintenance, which is critical in some environments (such as hospitals, for example).

7.1.5.2. Cyclomed Ion Source

The ion source from Cyclomed is developed in the context of an internal ion source for cyclotrons [15]. It tries to solve the problems derived from the use of PIG internal sources in cyclotrons by producing the plasma with a RF electromagnetic field, instead of the DC discharge characteristic of PIG sources, consequently reducing maintenance and interruptions in the operation of the machine. Because of its functioning mechanism Cyclomed source can be classified within RF discharge ion sources, with many particular characteristics due to the fact that this source is internal to the particle accelerator.

We can summarize the main advantages from the Cyclomed ion source as follows:

- First, the required maintenance is significantly reduced compared to that of other internal sources for particle accelerators. There are also less undesired interruptions in the performance of the machine.

- The presence of a coaxial resonator chamber allows for an increasing in the electric field intensity and easing ignition, therefore leading to a reduced energy consumption.

- In this ion source cathodes are not required to be at high temperatures (magnitude of around 2000 K), so instead of using high-resistance conductors with high electron emission characteristics, such as Tantalum, cheaper materials like copper can be used.

- In case of producing H^-, because of no high energy electrons are produced within the plasma, the extracted current is slightly increased.

- A better efficiency of H^- production / destruction equilibrium can lead to less H_2 gas consumption by the ion source and improvement of the vacuum inside the cyclotron chamber for a given beam current extracted.

7.1.6. References

1. https://cas.web.cern.ch/sites/cas.web.cern.ch/files/lectures/senec2012/scrivensdefinitionsionsourcesource.pdf
2. Introduction to plasma physics, R. J. Goldston, p. 1
3. Negative ion sources: Magnetron and Penning, D. C. Faircloth, p.24
4. RF Ion Sources, W. Kraus, p.14. Link: https://indico.cern.ch/event/150974/contributions/195741/attachments/154308/218380/KrausIonsource.pdf
5. ECRIS: The electron cyclotron resonance ion source, R. Geller, p.19
6. Laser ion source for heavy ion inertial fusion, Masahiro Okamura, link: https://www.sciencedirect.com/science/article/pii/S2468080X17301000
7. World Scientific Reviews of Accelerator Science and Technology, A.W. Chao
8. http://www.accelerators-for-society.org/about-accelerators/index.php?id=21
9. Link: http://www.accelerators-for-society.org/industry/index.php?id=8
10. Brittanica, “Mass spectrometry”, Louis Brown, link: https://www.britannica.com/science/mass-spectrometry
11. Link: https://www.marketsandmarkets.com/Market-Reports/particle-therapy-market-12809137.html
12. Link: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7281377/ , chapter 6
13. Link: https://www.marketsandmarkets.com/Market-Reports/mass-spectrometry-market-437.html?gclid=CjwKCAjwn6GGBhADEiwAruUcKl5qSf91ZXxPKVTH9ZBrokWvNcNLXFJF1CjeMVwrr24VeW4evjKJ_BoC0I4QAvD_BwE
14. Link: https://www.grandviewresearch.com/industry-analysis/medical-cyclotron-market
15. Low erosion ion source for cyclotrons, Rodrigo Varela patent number: 2 696 227

8 Future plans / Conclusion / relation to other IFAST work

I.FAST task 12.3 has finished in November 2023 with the following tasks achieved:

- Development of the IRISC (Internal RF Ion Source for Cyclotrons) idea and patent development
- Conceptual design of an IRISC ion source compatible with cyclotron AMIT, including geometry definition of the plasma chimney and the RF cavities and RF and thermal simulations.
- Detailed design of the IRISC ion source including the CAD solid modelling and the creation of 37 fabrication drawings.
- Development of tooling for the brazing of the ion source and for the shaping of the cooling and hydrogen tubes, including the CAD solid modelling and the creation of 27 fabrication drawings
- Fabrication of the IRISC ion source including machining of parts, cooling and hydrogen tubes shaping, brazing and assembly.
- Update of the IST (Ion Source Test bench) facility in Ciemat, including a complete redesign and fabrication of the vacuum chamber, a new RF based extraction system, new vacuum system, a new control system and a plasma analyser based on and spectrometer measurement of the plasma light.
- Low power test of the ion source
- Commissioning of the test facility systems, except the extraction system.
- Assembly of the ion source in the testing facility
- Start of the ion source and first plasma ignition. Initial analysis of conditions for start / stop of the plasma.
- Start of the conditioning of the extraction RF cavity

Additionally, a market analysis including the definition for the market context of cyclotrons with internal sources for industrial and clinical applications, the identification of current and emerging trends on internal ion sources and a benchmarking of internal ion sources was performed and is included in Annex I.

The following tasks could not be performed in the scope of I-FAST 12.3 task and will be performed in the future with other financing.

- Plasma characterization through the analysis of the visible spectrum of the light emitted.
- Ion source extracted current characterization.
- Correction of the incorrect brazing of one of the tubes

The task has been performed in a collaboration between CIEMAT Accelerators Unit, Health Care Division of General Electric and Cyclomed.

9 References

[1] J. Hopwood & J. Gregorio. “Microplasmas Ignited and Sustained by Microwaves”. Plasma Sources Sci. Technol. 23 (2014) 064002.

[2] H. Tawara et al. “Cross Sections and Related Data for Electron Collisions with Hydrogen Molecules and Molecular Ions”. J. Phys. Chem. Ref. Data, Vol. 19, No. 3, 1990.

[3] Low Erosion Ion Source for Cyclotrons, Rodrigo Varela. Patent number ES2696227B2.