National Centre for Fusion Technologies

Scientific-Technical Report

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Authors and Contributions

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Summary

The development of nuclear fusion is rapidly becoming a vital necessity in view of the continuing rise of the world's energy demand. Nuclear fusion offers a virtually endless source of energy that is both environmentally friendly and capable of meeting any foreseeable energy demand.

The progress of fusion constitutes one of the greatest technological challenges for humanity. Indeed, this field is one of the main areas of research of the European Union (EU), as was evident in June 2005, when the final agreement to construct ITER[1] (the *International Thermonuclear Experimental Reactor*) was signed, together with the USA, Russia, China, South Korea, Japan and India. ITER is an experimental reactor intended to demonstrate the scientific viability of fusion.

As the design of ITER is already defined, over the next 20 to 30 years the main focus will be on the development of technological components for future commercial reactors, rather than on basic plasma physics. The most important challenges for fusion research are the selection, development and testing of materials and the various elements for reactors, together with the design of energy extraction systems and tritium production methods.

At present, Spain has a unique opportunity to be at the forefront of this new technological field in Europe. However, there is a need for new facilities to simulate the extreme conditions to which materials and components will be exposed inside a fusion reactor.

The project outlined in this report describes the construction of a singular scientific and technological facility (the National Centre for Fusion Technologies -*TechnoFusión*) in the Madrid region, to create the infrastructure required to develop the technologies needed in future commercial fusion reactors, and to assure the participation of Spanish research groups and companies.

The Spanish scientific community has achieved an international recognition in the science and technology areas needed for the success of this ambitious project, as is evident from the results obtained by Spanish researchers in the fusion field over the past few decades. *TechnoFusión* intends to take advantage of the existing expertise of university research groups, public research institutions (*Organismo Público de Investigación, OPI*) and private companies. The performance of materials and components under the extreme conditions of a fusion reactor is largely unknown, and this is precisely what *TechoFusión* intends to explore. For this purpose, facilities are required for the manufacture, testing and analysis of critical materials. Additional resources are planned to develop and exploit numerical codes for the simulation of

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[1] ITER (originally the International Thermonuclear Experimental Reactor) is an international tokamak (magnetic confinement fusion) research/engineering project being built in Cadarache, France.

materials in special environments, to develop remote handling technologies and other areas related to the management of liquid metals.

In summary, *TechnoFusión* focus is the creation of infrastructures for the following research areas: 1) material production and processing, 2) material irradiation, 3) plasma-wall interaction (thermal loads and the mechanism of atomic damage), 4) liquid metal technologies, 5) material characterization techniques, 6) remote handling technologies and 7) computer simulation.

Therefore, *TechnoFusión* Scientific-Technical Facility will thus consist of a complex of seven large research areas, many of which are unique in the world, with the following main technical objectives:

1) *Material production and processing*. There are still some uncertainties about the materials that will be used to construct future fusion reactors, partly because it has not yet been possible to reproduce the extreme conditions to which such materials will be subjected. Therefore, it is of utmost importance to dispose of installations capable of manufacturing new materials on a semi-industrial scale and fabricating prototypes. Top priority materials include metals such as reinforced low activation ODS type steels (*Oxide Dispersion Strengthened steels*) and tungsten alloys. To manufacture such materials, equipment is required that currently is scarce or inexistent in Spain, such as a *Vacuum Induction Melting Furnace* (VIM), a *Hot Isostatic Pressing Furnace* (HIP), a Furnace for Sintering assisted by a Pulsed Plasma Current (*Spark Plasma Sintering*, SPS), or a *Vacuum Plasma Spraying* (VPS).

2) *Material Irradiation*. Even though the exact reactor conditions are only reproduced inside a reactor, it is possible to simulate the effects of neutrons and gamma radiation on materials by irradiating by ion and electron accelerators.

The effect of neutronic radiation will be characterized by combining three ion accelerators: one light ion accelerator of the tandem type for irradiating with He, with an energy of 6 MV, one light ion accelerator of the tandem type for irradiating with H (or D), with an energy of 5-6 MV, and a heavy ion accelerator of the cyclotron type, with k = 110, to implant heavy ions (Fe, W, Si, C) or high energy protons.

Additionally, a high magnetic field, between 5 and 10 T, must be incorporated into this facility in order to study the simultaneous effect of radiation and magnetic fields on materials.

The effects of ionizing *gamma* radiation will be studied using a *Rhodotron®* electron accelerator with a fixed energy of 10 MeV that will be shared with other *TechnoFusión* facilities.

3) *Plasma-wall interaction*. Inside a fusion reactor, some materials will not be subjected only to radiation, but also to enormous heat loads in the case of plasma disruptions. In view of this, both: i) stationary conditions due to the intrinsic reactor properties: high density, low temperature and high power and ii) violent transient events (called ELMs in plasma physics literature) must be reproduced. Therefore, it is essential to dispose of a device (which it will be called "plasma gun") to study plasma-material interactions simultaneously in steady state and transient regimes, thereby allowing an analysis of the modification of the materials and their properties in fusion reactors.

The mentioned plasma gun would consist of two main elements: i) a linear plasma device capable of generating hydrogen plasmas with steady state particle fluxes of up to 10^{24} $m^{-2}s^{-1}$ (i.e., of the order of the expected ITER fluxes) and impact energies in the range of 1-10 eV, and ii) a device of the quasi-stationary plasma accelerators (*QSPA*) type, providing pulses lasting 0.1-1.0 ms and energy fluxes in the 0.1-20 MJm^{-2} range, in a longitudinal magnetic field of the order of 1 T or greater.

These devices are connected by a common vacuum chamber, allowing the exchange of samples, and their simultaneous or consecutive exposure to the steady state and transient plasma flows under controlled conditions. Both devices will operate with hydrogen, deuterium, helium, and argon.

4) *Liquid metal technologies*. A number of, ITER, DEMO (*DEMOstration Fusion Power Reactor*)[2], and IFMIF (*International Fusion Materials Irradiation Facility*)[3] components will use liquid metals as refrigerants, tritium generators, neutron reproducers, moderators, etc., all of them under extreme conditions. Therefore, these applications need further research to be finally implemented in such installations.

The basic working scheme for this Facility in *TechnoFusión* is an arrangement of two liquid lithium loops, one of them coupled to the *Rhodotron®* electron accelerator to investigate the effects of gamma radiation on different conditions of the liquid lithium.

The main goals of this Facility are the studies of i) the free surface of liquid metals under conditions of internal energy deposition, and ii) the compatibility of structural materials and liquid metals in the presence of radiation. In addition, it will be possible to study the influence of magnetic fields on the cited phenomena as well as the development of methods for i) purification of liquid metals, ii) enrichment of lithium, iii) extraction of tritium, and iv) development of safety protocols for liquid metal handling.

5) *Characterization techniques*. Ambitious and well-understood research requires an accurate knowledge of the materials under study. Therefore, a range of techniques to characterize them under different situations is a key element in the global scheme of *TechnoFusión*. These techniques include mechanical testing (creep, nanoindentation, fatigue, etc.), compositional analysis (Secondary Ion Mass Spectrometry and Atomic Probe Tomography), and structural characterization (Energy Filtered Transmission Electron Microscopy, X-Ray Diffraction), as well as a number of material processing techniques (Focused Ion Beam Systems coupled to a Scanning Electron Microscope). Additional systems will be used to characterize physical properties (electrical, dielectric, optical, etc.).

Some of the above-mentioned techniques will be implemented to test the materials either in-beam –while being irradiating— or *in-situ*, inside the lithium loop. Needless to say, these techniques can also be performed before and after irradiation or before and after experiencing any other physical or chemical processes.

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[2] DEMO (DEMOnstration Power Plant) is a proposed nuclear fusion power plant that is intended to build upon the expected success of the ITER experimental nuclear fusion reactor.
[3] IFMIF is a planned high-intensity neutron reactor whose spectrum should be equivalent to that of a fusion reactor. The final design comprises two deuteron accelerators impinging on a liquid lithium target to generate nuclear stripping reactions to provide the desired neutron spectrum

6) ***Remote handling technologies*.** The conditions inside a fusion reactor are incompatible with a manual repair or replacement of parts. Therefore remote handling is indispensable. New robotic techniques, compatible with such hostile conditions, need to be developed; while existing techniques need certification in order to be applied at installations such as ITER or IFMIF.

TechnoFusión Facility will contribute to this knowledge with: i) a large installation for the prototypes manipulation such as: *Diagnostic Port Plug* of ITER, *Test Blanket Modules* of ITER and Modules of irradiation of IFMIF, and ii) an Irradiated Room coupled to the electron accelerator –*Rhodotron®*— in order to carry out validation, certification and characterization of remote handling tools and machines in an uniform ionizing field equivalent to ITER-DEMO trying to simulate the fusion reactor environment.

7) ***Computer simulation***. To study conditions that cannot be reproduced experimentally and to accelerate the development of novel systems for a future commercial fusion power plant, *TechnoFusión* will stimulate an ambitious programme of computer simulations, combining existing experience in the fusion field with resources from the National Supercomputation Network[4]. The goals include the implementation of the global simulation of a commercial fusion reactor, the interpretation of results, the validation of numerical tools, and the development of new tools. Another indispensable goal is the creation of a data acquisition system and the visualisation of results.

Based on the existing experience of research groups at Universities, Public Research Organisations and company research departments, *TechnoFusión* proposes the development of a large scientific infrastructure in order to make a significant contribution to the development of new technologies needed for the construction of commercial fusion reactors. The project described here will permit the generation of highly relevant technological knowledge for all types of fusion reactors, irrespective of the underlying concept (magnetic or inertial confinement).

The goal of TechnoFusión is to bring together sufficient human and material resources to contribute significantly to the development of a safe, clean, and inexhaustible source of energy for future generations.

[4] http://www.bsc.es/index.php. September 2009.

6. Plasma-Wall Interaction

6.1. Introduction

The operation of experimental fusion reactors in the coming decades and beyond (i.e., commercial reactors) will require expanding our knowledge concerning the behaviour of thermonuclear plasmas in magnetic confinement devices. Such knowledge involves understanding the relationships between operational parameters in present and future devices. For example, the integrated plasma flux impacting on the divertor tiles in a single ITER pulse typically corresponds to the integrated flux experienced over a whole year in present devices like JET. Similarly, the energy fluxes impacting the inner wall components of ITER during transitory events will exceed current values by one order of magnitude. Indeed, the energy content of ITER plasmas will be more than one order of magnitude (more precisely, a factor of 30) greater than that of present devices (such as JET), while the effective area of the inner wall components is only larger by a factor of 2. In addition, the corresponding fluxes in DEMO will typically be 5-10 times those of ITER. Consequently, significant advances are required in our current knowledge of plasma-material interaction, for which experiments are required.

Some of the main technological challenges for the operation of ITER are related to plasma-material interaction (related to first wall materials, limiters, or divertors) and the study of these issues is surely among the key measures of success of the project. Moreover, their impact on the design of DEMO is considerable, and in recent years the fusion community has therefore joined forces to study these phenomena. As a result, in 2002 the "EFDA Task Force", centred on the topic of Plasma-Wall Interaction, was created as the first Task Force of its kind in the EU. This Task Force has helped to channel the efforts of different EURATOM associations towards the study of topics such as the erosion of plasma facing materials, fuel (deuterium-tritium) retention in materials, the response to high thermal loads, the generation of dust and pollutants, material mixing effects in the first wall, etc. From the beginning, the Plasma-Wall Interaction Group at CIEMAT (whose members will constitute the *TechnoFusión* Plasma-Wall Interaction group) has participated in several of the above-mentioned studies. Here, it is mentioned a particularly relevant contribution on the subject of the removal of trapped tritium from reactor walls, and on mechanisms for carbon transport and co-deposition in ITER.

Many experiments have already been carried out in laboratories and fusion devices to study the behaviour of selected materials for the divertor (CFC and tungsten), and the first wall (beryllium) when the latter are exposed to high thermal loads or high particle fluxes, and how this behaviour is affected when they are previously irradiated by energetic particles (though not by 13 MeV neutrons, as would be the case in a fusion reactor). In general, it is found to be extremely difficult to extrapolate laboratory results to fusion devices, which is caused mainly by the complexity of the reactor conditions, where processes occur such as the formation of mixtures of the initial constituents, possessing very different chemical and physical properties from those of the original pure constituents. Even though evidence exists that the simultaneous action of these conditions (high thermal load, high particle flux, and radiation) can produce a synergy with unknown results, at this time no facilities exist capable of directly studying such possible synergies. Therefore, the main goal of the proposed Plasma-Wall Interaction Facility of *TechnoFusión* is to become the first facility in the world having the capacity of studying all these phenomena simultaneously.

Present research in this field indicates that the interaction of the proposed materials and expected plasmas in devices such as ITER and DEMO can significantly modify the material properties due to: i) the retention of hydrogen isotopes in the surface layer and the formation of chemical compounds as a result of reactions between materials used in the inner components of the reactor vessel, ii) changes in the structure due to the high temperatures occurring during operation, iii) high neutron fluxes damaging the surrounding materials, and iv) (in transitory events) structural modifications due to the very large power fluxes, leading to surface damage of the material (i.e., the melting of metals, sublimation of ceramics, sputtering of aggregates, etc.), and surface fractures that affect both the material properties and its resistance. These damages result in diminished thermal conductivity, reduced mechanical resistance, permeability, retention of hydrogen isotopes, etc.

Obviously, the study of these processes can be carried out in the present and future nuclear fusion devices, but often, these devices do not allow a proper study of the interactions, requiring the characterization of the plasma and the materials with sufficient accuracy. Furthermore, setting up the necessary test components to perform these experiments in fusion devices is often difficult or complex, requiring much time. These considerations, along with the impossibility of replacing test components in reactors, have spawned the development of experimental facilities, specifically dedicated to the study of the interaction of materials with the peripheral plasma in thermonuclear fusion devices, by simulating the properties of these plasmas in steady state and during transitory events.

At the moment, several laboratories have experimental facilities capable of reproducing the characteristics of fusion reactor plasmas to different degrees and using different approaches, and their interaction with materials, in either steady state or transient regimes, although no facility is capable of simulating both. The reason for this is that devices designed to study steady state phenomena, like PSI-2 (Humboldt University, Berlin), PISCES-B (California University, San Diego), and Magnum-PSI (under construction at the FOM-EURATOM association), are intrinsically limited regarding the generation of energy pulses similar to transitory events in fusion reactors (usually ~ MJm^{-2} on a sub-ms time scale). On the other hand, devices capable of generating transient energy pulses, such as the Quasi-Stationary Plasma Accelerator (QSPA) at the TRINITI laboratory of the Russian Federation (QSPA-T), or the device at the Institute of Plasma Physics in Ukraine (QSPA-Kh50), lack the possibility to generate plasmas that last more than 1 ms, due to the physical principles on which they are based.

The transitory events may occur at certain typical repetition frequencies. For example, edge localized modes (ELM) will have a frequency of about 1 Hz in fusion reactors, and can have a significant effect on materials, modifying their behaviour as compared to with steady-state plasmas. Thus, it is essential to dispose of a device (which it will be called “plasma gun”) to study plasma-material interactions simultaneously in steady state and transient regimes, under conditions relevant to a fusion reactor, thereby allowing an analysis of the modification of the materials and their properties in fusion reactors. This is the objective of the **Plasma-Wall Interaction Facility (PWI)** of *TechnoFusión* Centre. The mentioned plasma gun would consist of two main elements:

a) A linear plasma device, similar to the existing PILOT-PSI device, capable of generating hydrogen plasmas with steady state particle fluxes of up to 10^{24} $m^{-2}s^{-1}$ (i.e., of the order of the expected ITER fluxes) and impact energies in the range of 1-10 eV (although higher energies can be reached by polarizing the plasma with respect to the target).

b) A device of the QSPA type, providing pulses lasting 0.1-1.0 ms and energy fluxes in the 0.1-20 MJm^{-2} range, in a longitudinal magnetic field of the order of 1 T or greater.

These devices are connected by a common vacuum chamber, allowing the exchange of samples, and their simultaneous or consecutive exposure to the steady state and transient plasma flows under controlled conditions.

It is not yet decided what kind of materials will exposed to the plasma in ITER and DEMO, due to the incomplete knowledge of material behaviour under the extreme conditions of high particle flux, thermal loads, and neutron irradiation. The following issues are critical:

- The lifetime of the plasma facing materials
- Dust generation due to material erosion
- The in-vessel tritium inventory.

In spite of these uncertainties, and due to the time constraints of the project, a compromise has been reached for the initial phase of ITER, so that the divertor will be made of tungsten (in regions of moderate thermal load) and carbon (as a CFC). Due to the high degree of tritium retention in carbon scenarios, the substitution of CFC by tungsten in the reactor phase (D+T operation) is foreseen. However, the final decision depends on future results from the ASDEX-UG tokamak, now operating in a pure tungsten scenario, and from JET, fitted with an ITER-like wall. Such a wall includes a pure tungsten divertor, and uses beryllium as a vacuum vessel coating, in accordance with the ITER first wall proposal. Nevertheless, there exists a great difference between ITER (pulsed plasma) and DEMO (continuous plasma) regarding the total neutron dose, which will create uncertainties when extrapolating the results obtained in ITER to a continuous reactor. For these reasons, the research of materials under the cited extreme conditions constitutes one of the crucial issues of fusion research.

In recent years, research in laboratories possessing devices similar to those proposed for the *TechnoFusión* Plasma-Wall Interaction project has led to the discovery of new phenomena related to the first wall, with great potential for future application.

Mixed materials effects (in linear plasmas). These effects include the drastic reduction of the chemical erosion of carbon in the presence of beryllium, the formation of eutectic mixtures in the Be/W system with a melting point below that of pure W, the increase of tritium retention in beryllium when it forms part of carbides and oxides, the formation of W and Be carbides at the temperatures expected in the high thermal load region of the divertor, etc.

Thermal load effects (in plasma accelerators). The realistic simulation of material degradation in the divertor requires considering ELM's, with energy pulses greater than 1 MJm^{-2} lasting less than 1 ms, and with a repetition frequency of the order of 1 Hz. Although there are no experimental devices that can reproduce these conditions, it has been shown, in devices like QSPA, that material fatigue limits the maximum tolerable power in steady state after a specific number of ELM-like pulses. In the case of C (as a CFC) and W, the former experiences erosion of the PAN component (glue of the individual fibres) with loads exceeding 0.5 MJm^{-2}. For the latter (W), the erosion process leads to the ejection of liquid metal, whose subsequent behaviour depends on the presence of magnetic fields and the plasma pressure at the surface. The formation of liquid metal can also give rise to shortcuts between the rods included in the design of the high heat flux components of the divertor (macro-brush structures). For a series of pulses with thermal loads below those needed for material melting (again of the order of 0.5 MJm^{-2}), the micro-fissures have been observed to grow into macroscopic cracks that can lead to material fracture. This can also give rise to the formation of activated dust.

Synergetic effects between plasma species. The simultaneous irradiation of materials by the various main particle species emitted by the plasma (deuterium, tritium, helium, and neutrons) sometimes produces synergetic effects. A representative example is the formation of defects in a material and the consequent tritium retention caused by the combined effect of neutron damage and irradiation by a tritium containing plasma. With respect to neutron damage, in ITER, with an estimated irradiation dose of 0.6 dpa (displacement per atom), it is known that the amount of retention due to neutron irradiation on tungsten would not be very different from the non-irradiated case. However, the situation in DEMO could be radically different, so that this material and similar refractory metals should be avoided in the final design. Additionally, the simultaneous implantation of several species at high fluxes can enhance tritium retention: for example, a species with low solubility such as helium originates aggregates (bubbles) that act as trapping sites for the main species (D, T). Furthermore, the pressures occurring in these cavities can damage the material and eject it towards the plasma (blistering). The probability of diffusion and surface and volume recombination is strongly dependent on the temperature (which depends on the plasma impact), and therefore some divertor areas always have the right conditions for these phenomena to occur. For example, recently it has been found that helium irradiation of tungsten leads to the development of nanometric structures with a high capacity for tritium retention. Again, these studies were carried out in a linear plasma device similar to that proposed in this report.

Another synergetic effect is produced by the combination of temperature and metal implantation. In this case, the implantation of hydrogen isotopes at relatively low temperatures (below the embrittlement point of the material) entails a severe mechanical degradation of the material. The periodic exposure of this material to ELM-like thermal pulses can severely degrade its power handling capacity.

At present, no experimental device exists capable of simultaneously reproducing the above-described phenomena. Making the correct choice of plasma facing materials, and developing strategies for a long device lifetime, will be only possible if extreme conditions can be reproduced in the laboratory, similar to those expected in ITER and DEMO. Therefore, the construction of the Plasma-Wall Interaction Facility is essential for performing such important experiments for the fusion program.

Finally, the characterization of low temperature and high density plasmas, typical of the divertor of a future reactor, has its own intrinsic value, due to its complex atomic and molecular physics. Consequently, an additional benefit of the proposed linear plasma device is the development of diagnostic methods based on atomic and molecular physics (spectroscopy, mass spectrometry, probes, etc.), suitable for ITER and other future devices. This task requires producing continuous plasmas in a high magnetic field and with a high gas flux, and involves the management of superconductor coils and cascaded arc plasma sources capable of providing suitable high fluxes.

6.2. Objectives

A large number of important material related issues, identified in the course of the European Fusion Program, can be studied using known experimental techniques and methods for material modification. Some of these are:

- A study of the behaviour of materials relevant to ITER and DEMO at high particle fluxes of different species (H, D, He).
- A study of the behaviour of materials relevant to ITER and DEMO at high energy fluxes and at different temperatures.
- A study of the behaviour of materials relevant to ITER and DEMO at high particle fluxes from the plasma, with simultaneous high thermal loads.
- The effect of local magnetic fields and plasma pressure on the movement of liquid layers or gas clouds created by the plasma.
- The effect of sample orientation with respect to the plasma for the cited phenomena.
- A study of material mixing and its effect on the plasma-material interaction.
- The characterization and modelling of the effect of plasma irradiation of structural materials, shields, joints, welds, etc.
- The characterization and modelling of plasma-wall interactions for different kinds of materials.
- The characterization and modelling of plasma irradiation on insulating materials and diagnostic components.

The first and second of the above points require plasmas that are large enough to achieve saturation in the exposed material. It is also desirable that the particle flux directed towards the sample is sufficiently intense to facilitate the extrapolation of the results to the experimental conditions of ITER (see Table 6.1).

Table 6.1. Thermal and particle loads in ITER (1998 design).

Component **Material** **Area**	**Power flux ($MW{\cdot}m^{-2}$)**	**Particle flux ($DT{\cdot}m^{-2}{\cdot}s^{-1}$)**	**Energy (eV)**	**Neutron flux ($n{\cdot}m^{-2}{\cdot}s^{-1}$)**
First wall Be ~1000 m^2 –Charge exchange neutrals (E_{mean}<100eV)	0.5	10^{19}-10^{20}	100-500	<$2.3x10^{18}$
Limiter start-up Be ~10 m^2 – Direct interaction with plasma and high power flux during the starting-up and switching off of the plasma	~8	10^{21}-10^{22}	""	<$2.3x10^{18}$
Divertor target (*strike-points*) C 75 m^2 – High power and particle fluxes; energy deposition during disruptions and ELM's; electromagnetic loads during disruptions	<10-20 <40 (ELM's) <100(disrupt)	<10^{24}	1-30 (plasma temp.)	4-$6x10^{17}$
Divertor sides (*baffle*) W ~200 m^2 – Charge exchange neutrals (M_{edia}<100eV); direct interaction with SOL; power radiated from X point (i.e. MARFE's); possible power deposition during ELM's; electromagnetic loads during disruptions	3	10^{20}-10^{22}	> 3 (plasma temp.)	<$2x10^{18}$
Divertor Dome W 85 m^2 – Charge exchange neutrals(E_{mean}<100eV); power radiated from X point (i.e. MARFE's); energy deposition during VDE; electromagnetic loads during disruptions	3	10^{21}-10^{22}	>30 (plasma temp.)	<$1.1x10^{18}$
Divertor private flux region (liner) **W** **90 m^2** **–**Radiated power dissipated on the divertor; re-irradiated energy during disruptions; electromagnetic loads during disruptions	<1	<10^{23}	<1	~$4x10^{17}$

Similarly, the study of transient high thermal loads requires a pulsed high power plasma with pulses of a short duration, so that ELM[58] effects can be simulated.

[58] Edge Localized Mode: A transitory relaxation event of the edge plasma that produces a high energy flux to the wall.

In order to achieve the objectives related to steady state plasmas, a cascade arc plasma source is proposed, designed to reach conditions similar to those of ITER in steady state. The main shortcoming of such a device is that it requires a high magnetic field. Alternatively, a LaB_6 source may be used. The latter produces particle fluxes that are one order of magnitude lower, while requiring a weaker field and providing a larger plasma diameter. However, to simulate the integrated fluxes expected at ITER, it would be necessary to increase exposure times. As mentioned above, high flux plasmas in a device with superconductor coils would open the possibility of studying divertor-like plasmas.

On the other hand, the best way to produce short pulse and high power plasmas is to use Quasi-Stationary Plasma Accelerators (QSPA).

The goal of the proposed steady-state (or continuous) plasma device would be to produce a homogeneous plasma with a radius ≥ 4 cm, a particle flux of up to 10^{24} $m^{-2}s^{-1}$, an ion impact energy in the range 1-10 eV (enhanced by means of polarization), and a total length of 1 to 2 m. Such a plasma would interact with a material sample under controlled temperature conditions in the 200 to 1500 ºC range. For this purpose, the sample is to be integrated in a heating-cooling system that can handle the mentioned temperature range.

The main working conditions for the linear plasma are:

- Particle flux > 10^{24} m^{-2} s^{-1}
- Electron density > 10^{20} m^{-3}
- Electron temperature < 10 eV
- Neutral pressure < 10 Pa
- Working gases: H_2, D_2, He, Ar

And for the QSPA:

- Energy density per pulse < 40 MJm^{-2}
- Pulse duration < 0,5 ms
- Peak intensity < 100 GWm^{-2}

6.3. International status of the proposed technologies

6.3.1. Major international facilities for Plasma-Wall Interaction research

The international research groups currently working on Plasma-Wall Interaction are:

- TRINITI, Troistk, Russia
- Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine
- Universidad de Nuevo Mexico, Albuquerque, USA
- Efremov Institute, San Petersburgo, Russia
- Japan Atomic Energy Research Institute, Naka, Japan
- Forschungszentrum, Jülich, Germany
- Budker Institute, Novosibirsk, Russia

6.3.2. State of the art of Plasma-Wall Interaction Technologies

Below, there is a list of the designs of the main linear and pulsed plasma devices operating in the foremost international laboratories:

a) Stationary linear plasma devices (steady state)

Numerous linear plasma facilities are operating across the world. The following devices are especially relevant for Plasma-Wall studies in view of their parameters:

a) [i]*Nagoya University*, Japan
b) [ii]*Humboldt-Universität,* Department of Experimental Plasma Physics, Berlin, Germany.
c) [iii]University of California San Diego, USA.
d) [iv]*Kurchatov Institute*, Moscow, Russia.
e) [v]*FOM-Institute for Plasma Physics Rijnhuizen, Nieuwegein*, The Netherlands.
f) [vi]*Idaho National Laboratory*, Idaho, USA.

The main characteristics of these facilities are shown in Table 6.2. In addition, the operating schemes and brief descriptions are given below.

Table 6.2. Facilities of Linear Plasma / Divertor Simulator.

	NAGDIS-II[i] [6]	**PSI-2[ii]** [7]	**PISCES-A[iii]** [8]	**PISCES-B[iii]** [9]	**LENTA[iv]** [10]	**Pilot-PSI[v]**[11]	**Magnum-PSI[v] *** [12]	**TPE[vi] [13]**
Source	TP-D	PIG	PIG	PIG	e-Beam	CA	CA	PIG
Power [kW]	10.5	6.5	<10	-	7.5	45	270	-
Pressure at source [Pa]	10	0.1-1	0.1-1	0.1-1		104	104	0.1-1
Pressure at *target* [Pa]	0.1	0.01-0.1	10-3-1	10-3-1	0.2-7	1-10	<10	0.01
Ti *target* [eV]	50	<15	10-500	10-500	5	0.1-5	0.1-10	10-130
Te *target* [eV]	10	<30	<20	3-50	0.5-20	0.1-5	0.1-10	10-15
ni *target*[m^{-3}]	$6\cdot10^{19}$	10^{19}	10^{19}	10^{19}	10^{19}	10^{21}	10^{20}	10^{19}
Ionic flux to *target* [$m^{-2}s^{-1}$]	10^{22}	10^{22}	10^{21}-10^{22}	10^{21}-10^{23}	$5\cdot10^{21}$	$2\cdot10^{25}$	10^{24}	10^{23}
Energy flux to *target* [MW/m^2]	0.01	0.1	-	-	-	30	10	-
B [T]	0.25	0.1	-	0.04	0.2	1.6	3	0.2
Beam diameter at *target* [cm]	2	6-15	-	3-20	2.5	1.5	10	0.5

* Currently under construction. Expected parameters.

- **TPE (*Tritium Plasma Experiment*)**. This is a small size device whose main advantage is its capability to work with beryllium and tritium. Its configuration is similar to that of PISCES-B[59]. A picture of this device is shown in Figure 6.1.

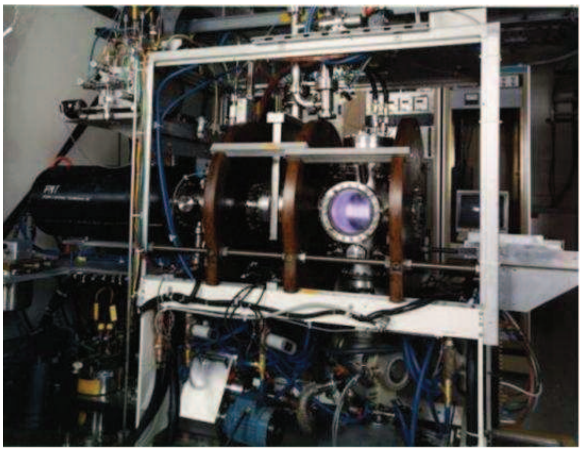
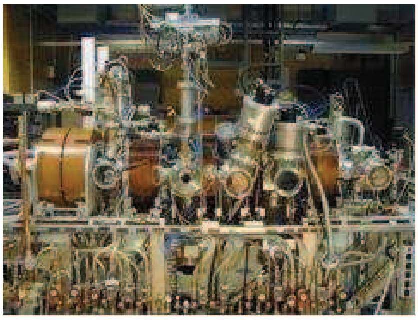


Figure 6.1. Picture of TPE linear plasma device installed at the Idaho National Laboratory, Idaho, USA.

- **PSI-2**. A diagram and a picture of this device[60] are shown in Figure 6.2.



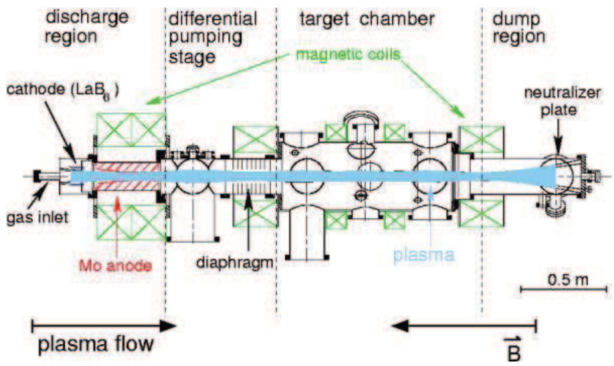


Figure 6.2. Linear plasma device at the Humboldt University, Berlin.

[59] http://nuclear.inl.gov/fusionsafety/experiments/star.shtml
[60] http://plasma.physik.hu-berlin.de

- **PISCES-B**. This is a device with a LaB_6 cathode, like TPE, PISCES-A, and PSI-2, that allows working with Be[61]. A diagram is shown in Figure 6.3.

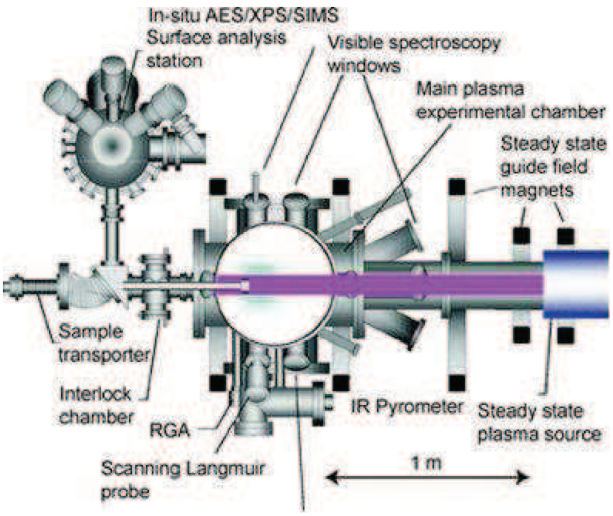


Figure 6.3. PISCES-B (a linear plasma device), University of California, San Diego.

- **LENTA**. This device[62] employs an electron beam to start the discharge. Figure 6.4 shows a sketch of the device.

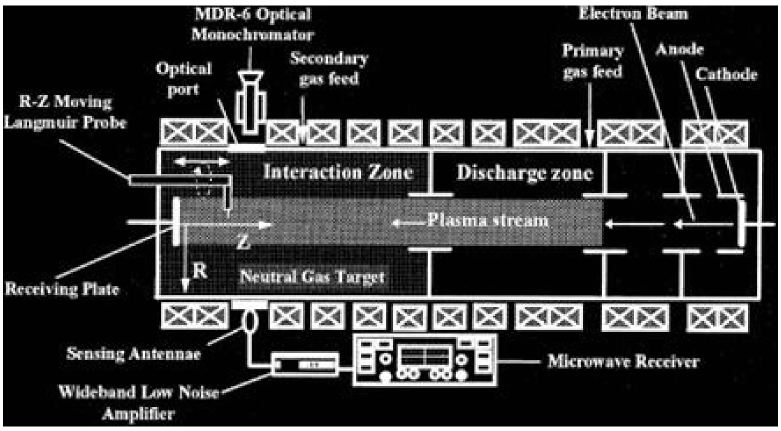


Figure 6.4. LENTA (linear plasma device), Kurchatov Institute, Moscow, Russia.

[61] http://www.pisces.ucsd.edu/pisces/Research/DivertorPlasmaSimulators/tabid/66/Default.aspx.
[62] http://www.kiae.ru/nsi/usnsi.htm#lenta

- **NAGDIS-II**. It uses a LaB_6 cathode combined with an intermediate electrode and an appropriate magnetic field that provides good plasma confinement. This allows improved insulation between the discharge and the sample chamber. Figure 6.5[63] shows a picture of this device.

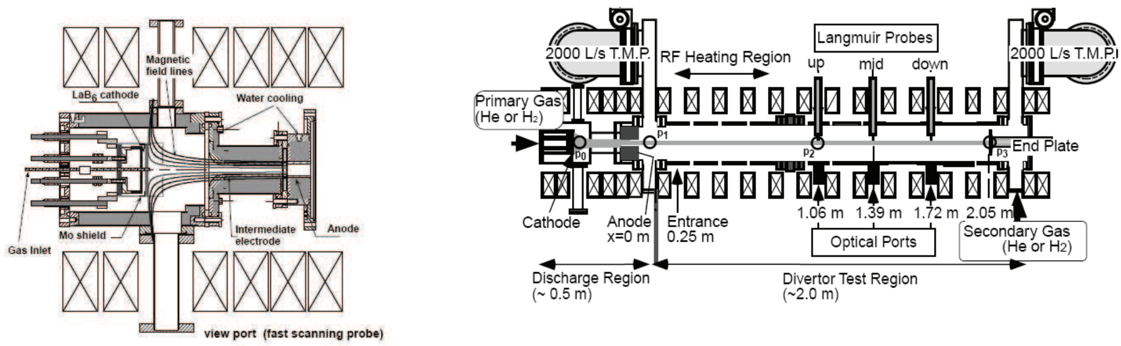


Figure 6.5. NAGDIS-II (a linear plasma device), Nagoya University, Japan.

- **Pilot-PSI**. The main characteristic of this device is that the plasma is generated by a cascade arc. This kind of system allows operating the arc at higher pressures and particle fluxes than Penning-like discharge devices. Figure 6.6 shows a picture and a sketch of this facility.

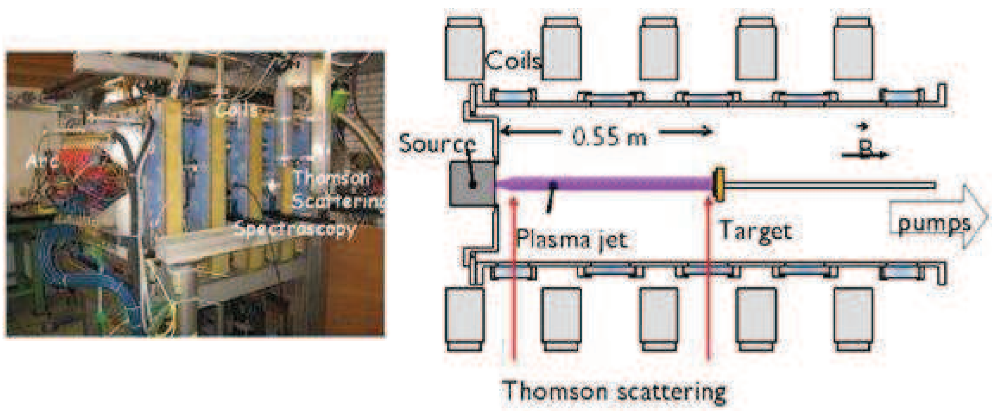


Figure 6.6. Pilot-PSI linear plasma device, FOM-Institute for Plasma Physics Rijnhuizen, Nieuwegein, The Netherlands.

[63] www.ees.nagoya-u.ac.jp/~web_dai5/english/NAGDIS_II.html

b) Quasi-stationary plasma accelerator devices (QSPA and QHPA)

The main high thermal flux or QSPA facilities currently in operation are:

a) [i]TRINITI, Troistk, Russia.
b) [ii]Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine.
c) [iii]University of Nuevo Mexico, Albuquerque, USA.
d) [iv]Efremov Institute, St. Petersburg, Russia.
e) [v]Japan Atomic Energy Research Institute, Naka, Japan.
f) [vi]Forschungszentrum, Jülich, Germany.
g) [vii]Budker Institute, Novosibirsk, Russia.

Table 6.3 summarizes the main characteristics of these facilities. Sketches and a review of their operational parameters are given below.

Table 6.3. High thermal flux devices at present.

D	E (MJ/m^2)	Pl (ms)	P (GW/m^2)	$MJ\cdot m^{-2}\cdot s^{-1/2}$	Ep (keV)	Dp (m^{-3})	B (T)	S (m)	A
MK-200UG[i] Pulsed plasma gun pulsed with drift tube[14]	15	0.04-0.05	300-400	~70	1.5 (ion)[1] 0.15[3]	$2\cdot10^{21}$ $(5\cdot10^{21})$2	2	0.065	a, b, c, d, e
MK-200CUSP[i] CUSP trap [14]	2	0.015-0.020	150-200	~15	0.8 (ion) 0.15[3]	$(1.5 - 2)\cdot10^{22}$	2-3	0.005	a, b, c
MKT-U[i] Pulsed plasma gun pulsed with drift tube [15]	1-2	0.03	30-60	>6	1.2 (ion)[1]	$6\cdot10^{20}$	2	~0.07	d, e
QSPA[i] **Kh50**[ii] Quasi-stationary plasma accelerator[16]	5-10	0.25-0.6	10-50	6-20	0.1	$<1\cdot10^{22}$	0-1	0.05	d, e
QSPA-Kh50[ii] Quasi-stationary plasma accelerator[17]	10-40	0.2	37-80	22-90	0,3 (ion)	$(2\text{-}8)\cdot10^{21}$	0-2	~0.04	d, e
PLADIS[iii] Plasma gun [18]	0.5-20	0.08-0.5	-	~15	0.1 (ion)	n/a	-	0.02	d, e
VIKA[iv] Quasi-stationary plasma accelerator [19]	2-30	0.09-0.36	20-84	<20	0.2	$>1\cdot10^{22}$	0-3	0.06	c, d, e
ELDIS[iv] Electron beam[15]	<50	0,05-0,06	2	>100	120[4]	$(2\text{-}4)\cdot10^{22}$	0-4	-	e
JEBIS[v] Electron beam [20]	2.5	1.5-2	2	~2	70[4]	n/a	0	>0.005	e
JUDITH[vi] Electron beam [21]	5-10	1-5	2-6	2-10	120[4]	-	0	~0.004	e
GOL-3[vii] Long mirror trap [15]	8-10	0.01-0.02	1000-1300	>50	1-3[3,5] (thermal) 20-10^3 (fast)	10^{21}	2-5	0.06	b, d, e

D = Device; E = Energy Density; Pl = Pulse Length; P = Power Density; Ep = Particle Energy; Dp = Plasma Density; B = Magnetic Field; S = beam Size, D = Beam Diameter; A = Applications
[1]Decreases to 300 eV at the end of the pulse; [2]Increases at the end of the discharge; [3]Electron temperature; [4]Electrons; [5]Non-Maxwellian distribution function with a large contribution of 800 keV electrons.
[a]Vapour dynamics in strong magnetic field at inclined target ("shielding") [b]Production of secondary radiation and its interaction with nearby surfaces, [c]Net radiation power to target surface, [d]Erosion (vaporization and/or ablation), [e]Ablation

- **QHPA P-50M**. Laboratory of Plasma Accelerator Physics. IMAPh NAS Belarus[64] . Figure 6.7 shows a diagram of this QHPA (Quasi-stationary High-current Plasma Accelerator) plasma gun. Its main characteristics are:

  - Discharge time 500 µs
  - Peak current 200 – 450 kA
  - Plasma velocity $(7 – 20)\cdot10^{6}$ cm/s
  - Electronic density $10^{16} – 10^{18}$ cm^{-3}
  - Electronic temperature 10 – 15 eV
  - Total energy 215 kJ
  - Vacuum chamber dimensions 0.8 x 0.8 x 4 m

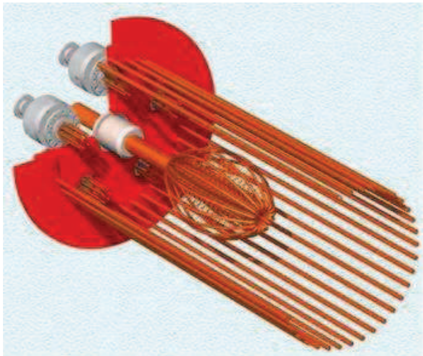


Figure 6.7. High thermal flux device QHPA, model P-50M, installed in the Laboratory of Plasma Accelerator Physics. IMAPh NAS Belarus.

- **QSPA Kh-50**. Institute of Plasma Physics. National Science Centre. Kharkov Institute of Physics and Technology. Ukraine[65]. Figure 6.8 shows a description of this plasma gun design. Several characteristics of these two QSPA devices are listed in Table 6.4.

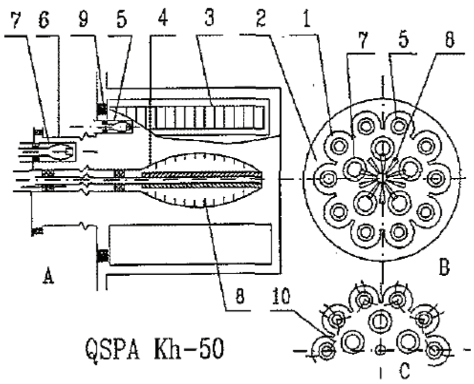


Figure 6.8. Quasi-stationary plasma accelerator QSPA Kh-50, at the Institute of Plasma Physics. National Science Centre. Kharkov Institute of Physics and Technology. Ukraine.

[64] http://imaph.bas-net.by/imaph/lpap/QHPA1.html
[65] http://www.kipt.kharkov.ua/en/ipp.html.

Table 6.4. Characteristics of QSPA Kh-50 and QHPA P-50M.

Device		P-50	Kh-50
First stage	Number of input ionization chambers	4	5
	Length of the drift chamber, cm	~20	80
Anode		Passive	Active
	Diameter (cm)	50	50
	Length (cm)	80	80
	Number of rods	36	(10)
	Number of anode ionization chambers	-	10
Cathode		Passive	Semi active
	Diameter (cm)	32	36
	Length (cm)	60	60
	Number of rods	16	20
Power supply	Capacitor bank C(μF)xU(kV); Wc (kJ)	5600x10 (22400x5); 280	7200x25; 2250
	Voltage achieved, Uc (kV)	8.5 (4.5)	15
	Discharge achieved, Id (kA)	≤600	≤800
	Pulse length, τ, ms	0.26 (0.55)	0.3
Vacuum chamber dimensions. Length (m) x Diameter (m)		4.0x1.0	10.0x1.5

- **MK-200 (UG y CUSP)**. Troitsk Institute for Innovation & Fusion Research. Russia[66]. Figures 6.9 and 6.10 show a picture and a diagram of this device, respectively.

Figure 6.9. Photograph of the quasi-stationary plasma accelerator MK-200 (UG y CUSP), at the Troitsk Institute for Innovation & Fusion Research. Russia.

66 http://www.triniti.ru/Triniti_eng/Base2.html#3

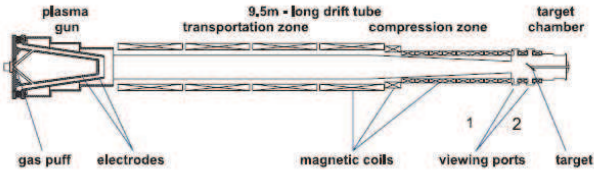


Fig. 1. Basic scheme of the MK-200 UG facility.

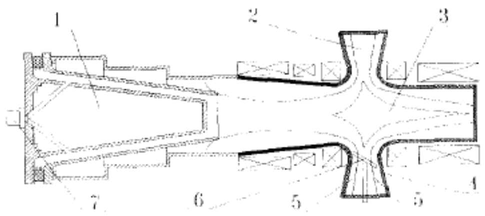


Fig. 1. Experimental facility MK-200 CUSP. (1) Plasma gun, (2) plasma escaping CUSP, (3) CUSP's plasma, (4) CUSP, (5) magnetic field lines, (6) target, (7) gas valve

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Figure 6.10. Diagrams of the device MK-200 (UG y CUSP), at the Troitsk Institute for Innovation & Fusion Research. Russia.

- **QSPA-T (TIN-1)**. Troitsk Institute for Innovation & Fusion Research. Russia[67]. A picture of this machine is shown in Figure 6.11.

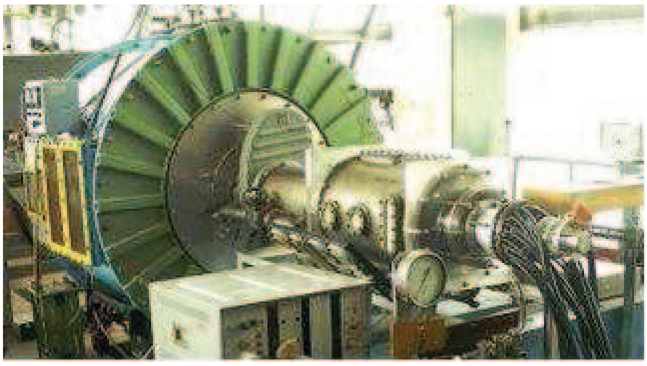

Figura 6.11. Photography of QSPA-T (TIN-1), *Troitsk Institute for Innovation & Fusion Research*. **Rusia.**

6.4. Projected facility

6.4.1. Steady state linear plasma device

Currently, two types of systems are used to generate plasmas in the continuous regime. There are devices that employ penning-like discharges and those that employ cascade arc discharges.

[67] www.triniti.ru/Triniti_eng/Base2.html#3

<u>Penning-like discharge devices</u>. In this case, the plasma stream is achieved by means of a hot cathode of LaB_6[68] and a hollow anode (molybdenum or another refractory material), creating a cylindrical quasi-neutral plasma that is confined by an axial magnetic field (~ 0.1 – 0.2 T). The plasma ends on a target sample at about 1-2 m from the source (see Figure 6.12). The plasma properties depend on the current between the anode and the cathode (typically in the range of 50-500 A), on the applied magnetic field, and on the gas pressure, controlled by the differential pumping of the different regions of the device by means of turbo-molecular pumps (common pressures are 0.1-1 Pa in the discharge region, and 0-1 Pa in the plasma-material interaction region). The impact energy of the ions can be adjusted by applying an electric potential to the irradiated sample (polarization).

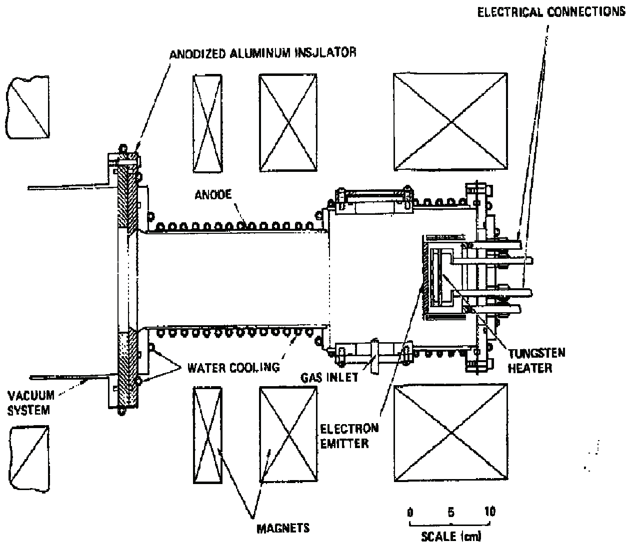

Figure 6.12. Description of a LaB_6 plasma source

The maximum flux achieved in this type of devices is around 10^{23} $m^{-2}s^{-1}$ for electron temperatures below 10 eV (without polarization). The energy flux to the target is less than $1MW/m^2$.

<u>Cascade-arc discharge devices</u>[69,70] consist of a chamber with needle-like tungsten cathodes, a series of copper elements (insulated by boron nitride plates), and a final anode element with a long channel (see Figure 6.13). All these components are water-cooled. The

[68] D.M. Goebel, Y. Hirooka, and T.A. Sketchley, "Large-area lanthanum hexaboride electron emitter," Review of Scientific Instruments, Vol. 56, 1985, pp. 1717-1722
[69] G. Van Rooij, "Laboratory experiments and devices to study plasma surface interaction," Fusion Science and Technology, Vol. 53, 2008, pp. 298-304.
[70] G.M.W. Kroesen, D.C. Schram, and J.C.M. de Haas, "Description of a flowing cascade arc plasma," Plasma Chemistry and Plasma Processing, Vol. 10, 1990, pp. 531-551.

hydrogen flux into the source is 0.5-3.5 slm (standard litres per minute), providing a constant pressure of ~100 Pa. The arc operates in the 60-300 A range and the applied voltage can reach 200 V. Each arc element receives a power of 2.5-3 kW (reaching up to 45 kW in a one-channel source, and up to 135 kW in a three-channel source), resulting in a total power at the source of ~40 MW/m^2.

These devices generate plasmas with a diameter of about 5 mm that are driven through a chamber with a background pressure of 1-5 Pa. It is possible to achieve fluxes above 10^{24} H^+ $m^{-2}s^{-1}$, and electron temperatures of the order of 1 eV. To maintain the high densities (10^{21} m^{-3}) corresponding to these fluxes, it is necessary to apply strong magnetic fields (~1 T) [8].

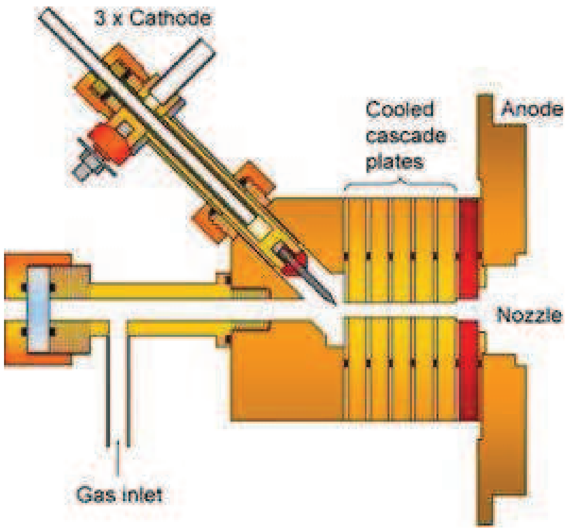

Figure 6.13. Drawing of a cascade arc plasma source.

In addition to the plasma source, a linear plasma device should have a series of diagnostic systems to allow the characterization of the plasma and the plasma-material interaction processes, such as:

- Several reciprocating Langmuir probes to determine the plasma temperature and density.
- Infrared thermography and calorimetry to determine the surface temperature at which the interaction occurs.
- Visible, infrared, and ultraviolet spectroscopy to determine the species that are formed due to the interaction in the plasma and in the target.
- Diagnostics of the background gas to determine the volatile species produced in the interaction, etc.

As a first step, the installation of a cascade arc source is planned, similar to the one employed at PILOT-PSI, generating a plasma jet with a diameter of 1.5 cm. This beam could be expanded by a suitable magnetic configuration to achieve irradiation of a greater sample area. This has the disadvantage of reducing the energy and particle flux at the target. In order to achieve a plasma beam diameter of around 5 cm in combination with high particle and energy fluxes, the implementation of a set of superconductor coils is also foreseen as the project unfolds. This will drive the plasma jet towards the sample.

At the moment, a collaboration exists between CIEMAT and FOM (The Netherlands) in the framework of EURATOM, for the development of cascade arc sources to generate plasma beams with larger diameters, namely in the 5-10 cm range. This work will be helpful for achieving the objectives proposed here, and for the development of new sources like MAGNUM-PSI (now under construction in FOM).

6.4.2. Quasi-Stationary Plasma Accelerator (QSPA)

The pulsed plasma device is based on a QSPA. In this device, a current is established between co-axial electrodes, ionizing the gas that is fed in and generating a plasma that is accelerated by the Ampere force induced by the current and an azimuthal magnetic field. This process can either be carried out in one stage (plasma generation and acceleration), or in two stages (plasma generation by a system of electrodes and subsequent acceleration). The QSPA is the magneto-hydrodynamic analogue of the Laval nozzle. Plasmas generated by this device can achieve energy fluxes of 0.1-20 MJm^{-2} in pulses of 0.1-1.0 ms, matching the expected values of transient events in fusion reactors (ELMs and disruptions).

A detailed diagram of one-stage QSPA coaxial electrodes is shown in Figure 6.14. The design of this plasma source is simpler than that of QSPA Kh-50, but more complex than QSPA-T (see Table 6.4). The outer electrode (the anode, consisting of a set of rods) has a diameter of 23-25 cm, while the inner electrode (the cathode, shaped like an ellipsoid) has a maximum diameter of 15-16 cm. The total length of the plasma source is approximately 60 cm. The whole system is contained in a vacuum chamber of 1.5-2 m length and 40 cm diameter.

The magnetic field, parallel to the vacuum chamber and of the order of 1 T, is generated by a set of coils. Its magnitude has to increase gradually from the plasma source (where ideally it has a value of around 0.1 T) to the sample, in order to avoid plasma loss due to strong field gradients.

Several compact valves will be operated simultaneously to feed in the gas, in order to achieve sufficient flexibility with regard to the plasma parameters and to reduce electrode erosion during long pulse operation. This flexibility is important when deuterium, helium, or other gases are used, apart from hydrogen.

Apart from systems that are common to every plasma generator, such as turbo-molecular pumps (with a pumping capacity of up to 1 litre of hydrogen per QSPA pulse), the operation of a QSPA device requires a specific power supply capable of handling short high power pulses. This type of power supply is typically based on a capacitor battery distributed into several sections, allowing the delivery of pulses of different lengths (0.25-0.5 ms). The capacitance should exceed 10 mF in order to achieve pulses of around 0.5 ms. The power supply should provide a current of 0.5-0.7 MA in different regimes, with a voltage of about 25 kV, in order to raise the ion temperature of the plasma, and as a means to increase the electronic temperature during the thermalization that occurs as the plasma is driven through an increasing magnetic field. These requirements imply an accumulated energy of 2.5-3 MJ.

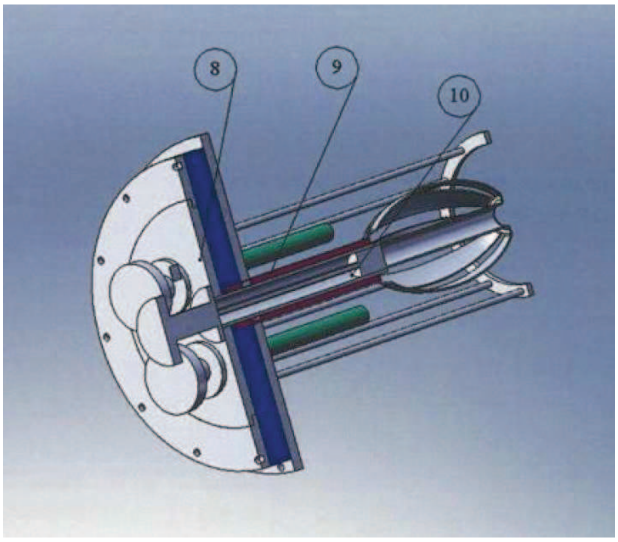

Figure 6.14. Diagram of one-stage QSPA coaxial electrodes proposed for *TechnoFusión*.

The sample exposed to the plasma has to be held in place by a setup capable of tilting it with respect to the plasma flow, varying the impact angle between 5º and 90º. Furthermore, the temperature of the sample needs to be controlled in the 200-1500 ºC range, prior to its interaction with the plasma.

Other systems essential for the correct operation of the QSPA device are:

- A synchronization unit (pulse generator), for which standard industrial solutions are available.
- A control system.
- Helmholtz coils, to produce the magnetic field of the discharge channel (these coils are not considered in the paragraph dedicated to the integration of both plasma generators).
- A commutator for discharge ignition (an ignitron, for example).

As with the linear device, the QSPA device requires appropriate diagnostic systems to characterise the plasma and corresponding data acquisition systems, such as sample thermography, high temporal resolution spectroscopy, calorimetry, probes, etc. A report written by the Institute of Plasma Physics QSPA group at Kharkov is included as an Appendix III.

6.4.3. Integration of the linear plasma device and the QSPA

The biggest challenge in the design of the *TechnoFusión* plasma wall interaction facility is the integration of both systems (the Linear Plasma Device and the QSPA) into a single device for the consecutive irradiation of samples. The linear plasma device will operate in steady state, while the QSPA will be pulsed. Their plasmas will be generated in their respective chambers, disposed in a collinear arrangement, to be transported by means of a magnetic field to the irradiation sample, which will be located between both devices.

The novel part of this proposal is the operation of both systems in a single machine, facilitating studies of plasma-wall interaction under fusion reactor conditions, including both steady state operation and transient events.

The proposed configuration which integrates both devices is a collinear one, where the sample chamber is located in the middle. This configuration takes advantage of a simple coil set-up, and moreover of the possibility of a low plasma angle of incidence irradiation over the sample. This low angle is relevant for the simulation of narrow incidence irradiation as in ITER divertor. The whole device will be composed of three independent chambers, which will be pumped independently and can be isolated one from each other by means of suitable valves. A movable sample holder would allow grazing incidence of plasmas on the target, alternating fastly between the steady and the pulsed plasmas. This configuration also allows other plasma-material interaction geometries, like normal incidence, without further re-arrangement.

Figure 6.15 shows the magnetic field generated by a coil set-up with the proposed configuration, where the QSPA device would be placed at the origin and the linear device (steady state) at the opposite end. The actual dimensions of the coils are under study, comparing diferent radius and their final cost, jointly with the geometric constraints they imposed. The following asumptions have been taken to carry out this analysis: coils are separated each other a distance equal to their radius and the magnetic field strength in the axis will be at least of 1.5 T. Furthermore, the QSPA's coils have to accomplish the KIPP design specifications detailed in AppendixIII , i.e., to generate a field of around 0.1 T at the source followed by a smoothly increasing field of aproximately 1 T/m up to reach its final value. As a preliminar result, the coil radius used to obtain Figures 6.15 to 6.17 is 20 cm.

The variation of the absolute value of the magnetic field along the axis of the device chamber is shown in Figure 6.17. It is seen that the magnetic field strength in the central part of the chamber, where the sample chamber will be placed, is quite constant, with a variation of around 1.3% in the axial field line without significant changes in a field line parallel to the axis at r=2.5 cm. A uniform magnetic field is crucial to obtain homogeneous plasma on the target.

Strong magnetic fields[71] are required in order to achieve high flux plasma operation (10^{24} $m^{-2}s^{-1}$) with ITER-relevant parameters. This imposes severe constraints on the final design of the whole device. Economically, superconductor coils can be competitive in view of the savings they produce in terms of power supplies and machine operation. This type of magnets

[71] B. de Groot et al., "Extreme hydrogen plasma fluxes at Pilot-PSI enter the ITER divertor regime," Fusion Eng. Design 82 (2007): 1861-1865

can be employed in places where a strong and continuous magnetic field is required. If copper coils are used (combined with superconducting coils for the high field side), a water-cooling system is needed, although in pulsed systems (with long pulses) liquid nitrogen can also be used as a coolant, which has the advantage of reducing the power requirements for operation.

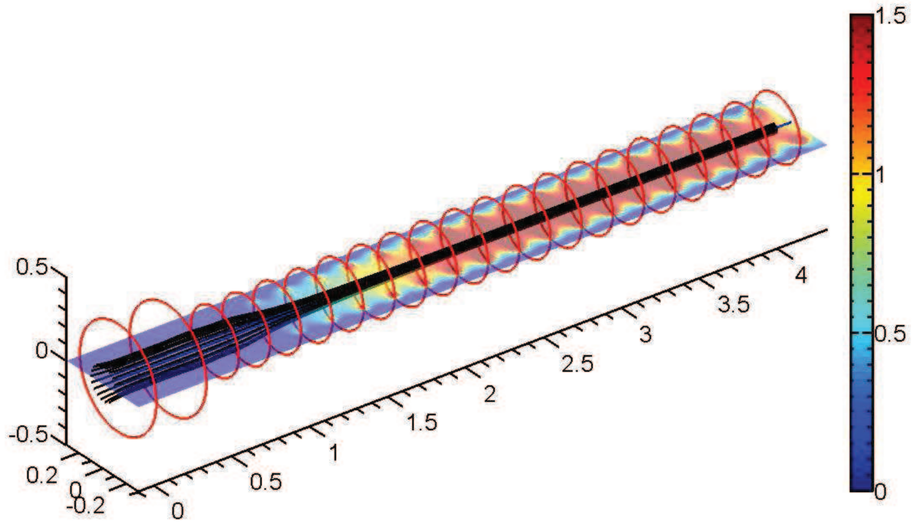

Figure 6.15. Proposed magnetic configuration for the integration of the linear plasma device and the QSPA. Red circles indicate the coil positions.

Due to the strong magnetic fields used in this facility a special care will be taken with the magnetic strength in the surroundings of the device (see Safety section). Concerning to this point, a map of the magnetic field around the device is shown in Figure 6.16, superimposed over a plane of a possible laboratory building. The level of 0.5 mT, which is a safety limit, appears as a red line in Figure 6.16, and is totally enclosed by the laboratory room.

The vacuum chambers will be designed using Monte Carlo codes like DS2V 4.5, developed by G. A. Bird (Figure 6.18).

Given the spatial restrictions imposed by the coils, the vacuum chamber will be partitioned into sections and designed to maintain a background pressure of the order of a few tenths of Pa. The gas feed will introduce gas at a rate of a few tens of slm (standard litre per minute), so that the most difficult case (the linear plasma device) will require at least three pumping regions with a capacity of several thousands of litres per second. Appropriate pumps (roots, turbo-molecular pumps, etc.) will be chosen to maintain the pressure in each section of the chamber. All vacuum systems will be located underneath the machine, so that the facility will consist of two levels.

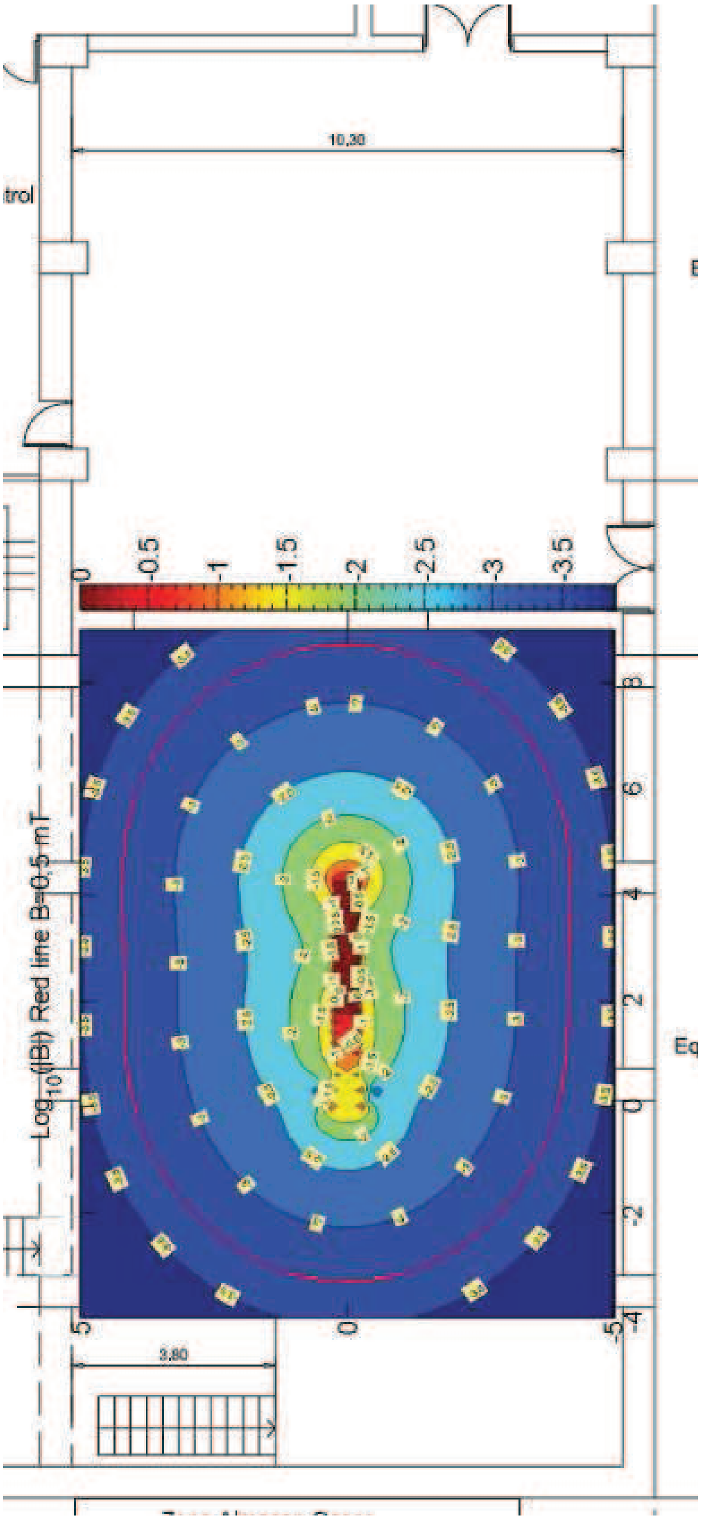

Figure 6.16. Top view of the magnetic field generated by the set-up from Figure 6.15, with its strength on the laboratory ground level. The red line indicates the value of 0.5 mT.

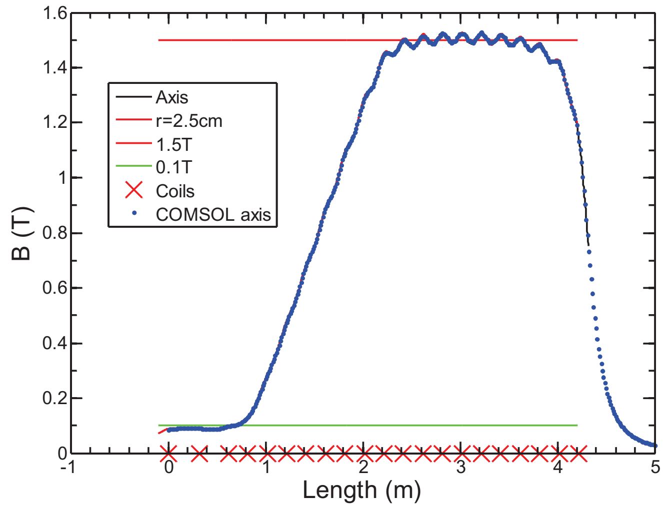

Figure 6.17. Magnetic field amplitude along the machine axis (black line), and along a field line parallel to the axis at r=2.5 cm (red line). Cross simbols indicate the coil positions.

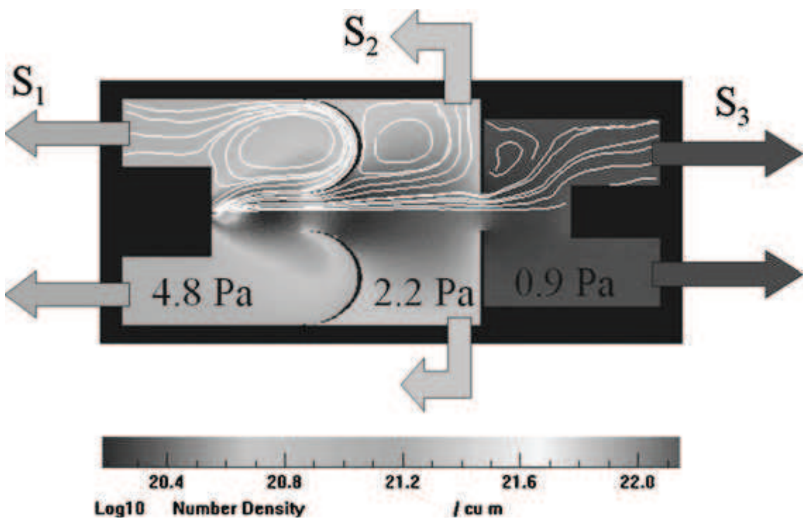

Figure 6.18. Simulation of the vacuum system using the software DS2V, applied to the MAGNUM-PSI facility [72]

[72] Van Eck H, Koppers W, et al, Fus. Eng. Design 2007;82 1878

All the devices described above are feasible and based on existing technology. Once this proposal is approved, a detailed design of these new devices will be made in order to optimize the solutions for several problems and minimize the differences of the proposed systems with respect to fusion reactor conditions. This process includes: improving the homogeneity of the linear plasma, increasing the impact energy of the ions and electrons in the QSPA, and reducing the plasma density. Moreover, the innovative part of this proposal (operating both plasma devices on the same sample, facilitating plasma-wall interaction studies under reactor-relevant conditions, including both steady state and transient events) requires the integration of two separate plasma production systems. The achievement of this integration will require further detailed studies, but the present report provides a conceptual solution for the problem of irradiating samples by both a steady state plasma and high thermal load pulsed plasmas.

The design of the plasma gun (QSPA) is fixed, but the design of the linear plasma device is open, the next design phase involving the choice of the type of coils. Preferably, the source will be a cascaded arc, although it is also possible to use a modified LaB_6 source, depending on the available budget.

6.5. *Experimental capacity*

The facility proposed in the present report can be used for a wide range of studies, some of which are not even directly related to nuclear fusion technologies. Table 6.5 shows a list of some key experiments that can be performed in the PWI Facility of *TechnoFusión*. Possible applications can be classified according to the adopted approach, as described below.

Table 6.5. Main fields of interest for PWI Facility.

Linear Plasma Device	QSPA	Combination	Irradiated material by ion beams
√ Power deposition experiments √ Chemical erosion √ Tritium retention √ Mixed Material √ Liquid metals in magnetic fields + plasma exposure	√ Transient thermal loads √ Fatigue after repetitive thermal shocks √ The behaviour of liquid layers in magnetic fields after thermal shocks √ Vapour shielding	√ Fatigue Experiments √ Tritium retention under steady state and transient loads √ The alteration of physical properties	√ The alteration of physical properties after irradiation √ Tritium retention after irradiation

6.5.1. Development of plasma diagnostics and training in associated technologies

Linear plasma devices are plasma generators that provide easy access to the plasma (without the geometrical constraints typical of stellerators or tokamaks) and produce long duration plasma beams. These characteristics simplify the development of diagnostics ultimately destined for larger machines, and associated techniques. This simplification constitutes an opportunity both for the optimization of technical aspects and training. Some appropriate diagnostic techniques are: Spectroscopy (active and passive), electric probes (Langmuir, Mach), retarding field analyzers and molecular beam diagnostics.

6.5.2. Research into first-wall materials

The PWI plasma devices described above are specifically designed for studies on first-wall materials for fusion reactors. These studies will focus on the following issues:

1. The long-time effects of irradiation by highly energetic plasma on a test sample. Studies of erosion, fatigue, etc.

2. The effects of high power pulsed loads (higher than the maximum load specifications for the material). This study can be performed using irradiation by a pulsed magnetized plasma (QSPA), and involves the observation of certain known but scarcely studied phenomena, like surface power shielding due to vaporization , the dynamics of melted layers, etc.

3. Studies of liquid materials (e.g. Li) are important because of their attractiveness as a first-wall material for high power handling in a future reactor. An additional difficulty affecting the application of such materials is that they are subject to magneto-hydrodynamic forces. The study of this issue requires interaction with the planned Liquid Metal Facility at the *TechnoFusión* Centre.

4. Analysis of material erosion. The latter may be caused by *ion* impact on the material surface, or by chemical reactions between the material and hydrogen atoms (chemical erosion). This is of special relevance for carbon-based materials.

5. Tritium retention studies (using non-radioactive isotopes). The amount of tritium accumulated in a fusion reactor has to be controlled and kept below safety limits (the amount of tritium permitted in the ITER vessel is 700 g). Studies on the retention of hydrogen isotopes (involving mechanisms such as diffusion, defect trapping, co-deposition with previously eroded material, etc.) can be carried out in linear devices.

6. Mixed materials effects. The fusion reactor environment is highly complex due to the presence of different materials. As a consequence, the first wall materials will be contaminated and mixed with others, changing their physical properties (behaviour under thermal loads, tritium retention, etc.)

7. Studies of irradiated samples at the Material Irradiation Facility, using high power particle fluxes in steady state, as well as high power fluxes combined with pulsed particle fluxes. The possibility of performing such studies make the PWI Facility into a unique facility, capable of managing the three most relevant problems related to the power inside fusion reactors simultaneously: irradiation damage, high energy and particle fluxes in steady state, and high thermal loads produced in transient events.

6.5.3. Plasma-wall interaction studies

The interaction between plasma and the wall produces a great variety of phenomena. For example, atomic physics processes at the first wall determine the plasma edge profiles. These processes include mechanisms such as gas recycling at the surface, impurity transport through the plasma, etc.

6.5.4. Plasma physics research

Low temperature plasmas are suitable for fundamental plasma physics studies involving MHD, turbulence, etc., the results of which can be compared to simulations, which is facilitated by the simple device geometry. These studies can also be of special interest for the training of research staff.

6.5.5. The study of materials under extreme conditions

High power fluxes in an aggressive environment (with the possibility of injecting corrosive gases like oxygen) allow the study of materials under extreme conditions, which is of interest for various fields of research (technology for the aerospace industry, power electronics, etc.[73]).

6.6. Layout, supplies and safety requirements

The availability of a set of measurement techniques and simulation methods related to the fusion reactor environment (high thermal loads, irradiation, etc.) in a single laboratory creates an important added value for the proposed facility, which would be unique in Europe and in the world. However, it also implies that the facility must have a flexible organization, allowing it to execute diverse experiments in different experimental areas. Therefore, special attention must be paid to this issue in the design of the facility.

[73] ExtreMat http://www.extremat.org/

(I) Space and buildings

The spatial needs for the activities of the PWI Facility of *TechnoFusión* are:

- One building (100 m^2 and 7 m height) to house the linear plasma device and the QSPA, as well as their vacuum systems.

- One auxiliary building to house the power supplies for coil operation and the plasma sources of both devices (100 m^2).

- One 40 m^2 room to house the equipment for the analysis and control of the materials irradiated by the plasma, and to assemble the diagnostics that will be installed in the machine.

- One 80 m^2 room to house the control systems.

- One 30 m^2 workshop.

- One 40 m^2 warehouse.

About installation:

(a) Electrical installation:

One high power supply will be required for the plasma sources of the devices. An additional and independent supply is needed for the vacuum systems and cryo-coolers (the latter only if superconductor coils are used).

The laboratory will be equipped with power sockets to supply power to the peripheral equipment (i.e., diagnostics, computers, etc.)

(b) Water distribution network:

A water supply is required for cooling the equipment (copper coils, vacuum systems, etc.). In addition, a closed-circuit cooling system may be needed, depending on the cooling specifications of the equipment.

(c) Compressed air and pressurized gas:

The operation of the machine requires several high-pressure gas feed lines (hydrogen, methane, ammonia, oxygen, etc.). Correspondingly, appropriate gas detectors and alarms must be installed in the building where the devices are housed, which will also have to be properly vented.

A supply line of compressed air is also needed to run pneumatic devices. The same line will be used for routine tasks associated with the installation of diagnostics.

(II) Safety

The hazards in the PWI Facility are mainly of an electrical and chemical nature (inflammable, combustive, and/or toxic gases), or associated with experimental activities (the use of lasers, etc.).

The PWI Facility will need high power electrical supplies and strong magnetic fields for its operation. The high power supplies should be electrically insulated and placed inside Faraday cages, with all the necessary security systems for safe operation (cut-off switches, blockers, etc.), preventing access when the systems are active. All components must be grounded when people access the high power supplies and experimental devices. Moreover, due to the prevailing strong magnetic fields of up to 1 T, access to the experimental area will be restricted when the magnetic field is on. The exposure to strong magnetic fields has no documented permanent effect on health[74], so that it is possible to work in locations with fields of up 2 T. However, the WHO recommends time-weighted averages not exceeding 200 mT during the working day for occupational exposure, with a maximum value of 2 T. Therefore, warning signs will be installed indicating the presence of strong magnetic fields, along with entry prohibition signs for people with pacemakers, ferromagnetic implants, or other electronic devices. All these signs will be placed in areas with fields below 0.5 mT. Finally, stray tools and/or ferromagnetic elements will be prohibited in areas where the field exceeds 3 mT, as these objects can be propelled by the field, damaging equipment and/or harming people.

Different types of gases will be used in the PWI Facility (inflammable, combustive, toxic, etc.). The gas supplies will be located in separated areas, which will be properly vented, in accordance with their hazardous potential, and sheltered from any sources of heat and direct sunlight. The electrical installation in storage areas of inflammable gases, if any, will comply with the corresponding legislation. Empty and full gas cylinders will be stored separately in different areas. The gas feed lines will consist of hermetically sealed lines arranged in a sufficiently flexible manner while complying with security requirements. Finally, gas detectors (for hydrogen, methane, acetylene, and oxygen), fire detectors, and the corresponding fire protection will be installed inside the experimental hall.

The use of cryogenic liquids in the PWI Facility constitutes another possible hazard. The main risks are cold burns and asphyxia.

The handling of irradiated samples from the Facility of Material Irradiation implies further safety considerations. These samples should be stored in controlled areas until their activity decays below the exemption limits[75]. Materials considered candidates for plasma

[74] WHO “Electromagnetic Fields and Public Health”. http://www.who.int/mediacentre/factsheets/fs299/en/index.html

[75] *Consejo de Seguridad Nuclear (Council for Nuclear Safety)*, instruction of February 26, 2003, number IS-05, establishing the exemption limits for nuclides according to Tables A and B of Annex I of the Royal Decree 1836/1999, Published in BOE nº 86, April 10, 2003

facing materials, mainly carbon based materials and tungsten, are most likely to be studied in the Plasma-Wall Interaction Facility. For carbon, the storage time will be several days, since the main radioactive isotope produced by irradiation is N^{13}, with a half-life of ~ 9.9 minutes, so that its activity drops to 3 orders of magnitude below the exemption limit in a few days. In the case of W, mostly rhenium isotopes are produced. Re^{183} has a half-life of ~70 days, so that these samples will need to be stored for months before their activity decays to acceptable values. If possible, the irradiation parameters should be adjusted to minimize storage time.

The purpose of storage is to reduce the activity of the irradiated samples to a level at least two orders of magnitude below the exemption limits. In this way, the activity levels will not exceed the threshold for a supervised area in the current legislation, even if the sample is lost inside the vacuum vessel.

The activity of the samples used by the PWI Facility will be monitored by means of the following proposed measures: a) the activity of the irradiated samples will be measured after the estimated storage time, to confirm that the required activity level has been reached; b) laboratory staff handling the samples will use dosimeters, and masks when performing tasks inside the machine. In addition, the cited staff will be subject to routine medical control; c) the contamination of the inner wall of the vacuum vessel will be tested periodically by performing surface activity measurements, which needs to be kept well below the values corresponding to a supervised area (0.04 Bq/cm^2 for alpha radiation and 0.4 Bq/cm^2 for beta and gamma radiation); d) waste products, such as oil from vacuum pumps, or used samples, will be classified and processed as low activity waste; e) as an additional safety measure, the experimental area may be delimited by screens, with access control and specific safety measures.

Finally, since this is an experimental facility, the risks inside the PWI Facility may vary during its operational lifespan. Therefore, an appropriate reconsideration of the safety measures for equipment and personnel will have to be undertaken regularly.

Appendix III: R&D for the Quasi-Stationary Plasma Accelerator (QSPA) for *TechnoFusión* Facilities

NATIONAL SCIENCE CENTRE "KHARKOV INSTITUTE OF PHYSICS AND TECHNOLOGY"

INSTITUTE OF PLASMA PHYSICS

R&D for the Quasi-stationary plasma accelerator (QSPA) for *TechnoFusión* Facilities

Part 1: Basic specifications for the QSPA device

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May 2009

Abstract

This report analyzes the definition of the basic design specifications of the Quasi-stationary plasma accelerator (QSPA) for the *TechnoFusión* Facility in Madrid. The final goal of this effort is the deployment of a new combined plasma device for studying the material damage caused by a fusion-grade plasma and the role played by ELMs. In this facility, such situation is simulated by means of a pulsed linear plasma. The facility will provide a better understanding of material behaviour under irradiation by a fusion-grade plasma, and allow quantifying the effects. The proposed new device is an appropriate combination of a QSPA and a steady-state linear PSI device. Below, it will be referred to this newly designed QSPA plasma source as QSPA-SLIDE – where the latter stands for Spanish LInear DEvice.

A general design is made of the *TechnoFusión* QSPA-SLIDE plasma source . The electrodes are assumed to be of the profiled rod type. The main dimensions of the plasma source elements are established.

Plasma flow is calculated for the chosen accelerator geometry on the basis of an MHD model, using 2 different approximations.

Various gas feed schemes are considered for the plasma accelerator. A combination of gas supply at the end and gas injection from the cathode region is chosen.

The effects of applying a small external magnetic field in the discharge region (by means of Helmholtz coils surrounding the plasma accelerator) are analyzed. It is concluded that a longitudinal magnetic field of $0.1.B_{int}$ enhances the streaming stability of the plasma and facilitates the entry of the plasma into the external B-field of the L-shaped vacuum chamber of the *TechnoFusión* facility.

The basic specifications of QSPA-SLIDE device are established. Key parameters of the various QSPA systems are determined.

The electronic characteristics of the power supply systems for the various elements of the QSPA-SLIDE device are calculated.

1. Introduction

The goal of this report is to establish the basic design specifications of the Quasi-stationary plasma accelerator (QSPA) for *TechnoFusión*. The global objective of this effort is the deployment of a new combined plasma device for studying material damage caused by a fusion-grade plasma and the role played by ELMs [1,2]. These effects are simulated by means of plasma streams, in order to obtain a better understanding of material behaviour under irradiation by a fusion-grade plasma, and allow quantifying the effects. The proposed new device is an appropriate combination of a QSPA and a steady-state linear device (we will refer to this newly designed QSPA plasma source as QSPA-SLIDE – where the latter stands for Spanish LInear DEvice).

The first stage of this activity involves a computational and experimental study, as well as a general analysis, oriented towards the design of the advanced quasi-stationary plasma accelerator (QSPA-SLIDE), including the configuration of the electrodes, the geometry of the nozzle, insulators, gas valves and various basic components, necessary for the adequate operation of the QSPA-SLIDE device. Also, studies are made of MHD plasma flows in the QSPA channel, for different geometries of the nozzle, subject to their compatibility with the external magnetic field.

The next stage of this activity will be executed after approval of the present report in the framework of part 2 below, focused on establishing the detailed specifications of the design of the QSPA facility and executing the corresponding studies, drawings and calculations, documented in the QSPA-SLIDE technical reports.

This report consists of two main parts. The first part describes the general considerations and the physical ideas and principles that underlie various design features and dimensions of the proposed QSPA-SLIDE device. The focus will be on the most relevant issues in order to provide clarity for physicists who were not involved in any preliminary QSPA studies, and will avoid unnecessary complications, omitting some details that are less important at this stage and that can be taken into account during the posterior detailed design of the components.

The second part of the report concerns key elements of QSPA-SLIDE, general design features of the plasma source, and component descriptions. Some cost estimations and characteristics of various components are also presented.

2. Main principles of QSPA

The general scheme of a typical QSPA acceleration channel is presented in Fig. III.1. A quasi-steady-state plasma flow is obtained in a profiled acceleration channel between two electrodes. Neutral gas is injected through the entrance of accelerator by means of electronically operated gas valves. The resulting discharge current in the acceleration channel produces an azimuthal magnetic field (Fig. III.1). The interaction between the discharge current and the azimuthal magnetic field results in an Ampere force $F = \frac{1}{c} j \times H$ that accelerates plasma.

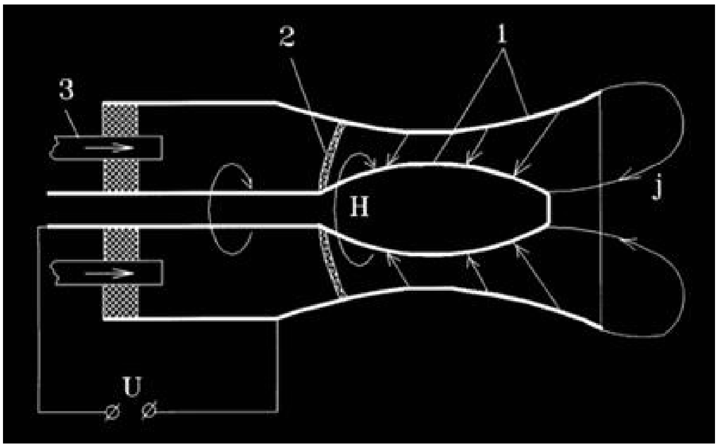

Figure III.1. Scheme of a QSPA acceleration channel: 1 – electrodes; 2 – ionization front; 3 – gas injection.

The acceleration by the Ampere force can also be considered as being due to the difference of magnetic pressure $P_m = \frac{H^2}{8\pi}$ along the acceleration channel. From this point of view, all the equations describing the plasma flow in the acceleration channel under the influence of the Ampere force look like the equations for gas flow in the magneto-hydro-dynamic analogue of the Laval nozzle, where magnetic pressure is applied instead of hydrodynamic pressure. Thus, one may estimate the maximum value of the plasma stream velocity achieved at the exit of the acceleration channel by: $\upsilon \propto \sqrt{P_{m,0}/\rho_0} \propto H_0/\sqrt{4\pi\rho_0} \propto C_{A0}$ where $P_{m,0}$ is the magnetic pressure in the entrance cross-section of the acceleration channel, ρ_0 is the plasma density and C_{A0} is the Alfvén velocity at the entrance cross-section of the acceleration channel.

However, this simple consideration is not capable of handling both stationary and pulsed operation. In this respect, both types of accelerators have to operate similarly. Pulsed plasma accelerators (plasma guns) have been designed and studied for many years in many different laboratories, and their efficiency limit has been established [3,4]. For maximum efficiency, it is necessary to establish the energy transfer time from the capacitor bank to the gun and the time needed for plasma motion along the acceleration channel. Increasing the energy content of the power supply systems, usually capacitor banks, is not a problem, but with increasing energy the energy transfer time also grows. Therefore, it is desirable to increase the time needed for plasma motion along the acceleration channel, and thus to increase the length of the plasma gun. An increased length of the plasma gun and of the time needed for plasma motion along the channel also increases the duration of the interaction of the plasma stream with the gun electrodes and, as a consequence, impurities are emitted from the electrodes into the plasma stream, so that the plasma stream parameters degrade. So, on the one hand, one would like to increase value of L/r to achieve maximum efficiency, where *L* is the length of the acceleration channel and *r* is the radial dimension of the acceleration channel, in order to provide an increased time for plasma motion along the channel. But on another hand, one needs a small value of L/r to decrease the level of impurities emitted from the gun electrodes into the plasma stream. Thus, the requirements for L/r are conflicting.

The most promising device, from the point of view of achieving the required highly energetic plasma stream and a maximum efficiency of the plasma source, is a steady-state or quasi-steady-state plasma accelerator. In such a device, the requirements regarding the energy transfer from the power supply system to the acceleration channel are not very strict.

The first quasi-steady-state plasma accelerators, or magneto-plasma compressors, based on this simple theory, were designed and manufactured at the Kurchatov Institute, Moscow, Russia. However, the first experiments carried out with such a device were not successful. In particular, the plasma stream velocity was much less than what was predicted from elementary theory. Very large potential jumps were observed in regions close to the electrodes. The electrical current flowing from anode to cathode slid along the electrode surface, and as a consequence plasma flow was halted and impurities were emitted from the electrodes into the plasma stream [3, 4]. All these phenomena resulted in the annulment of the gradient of the magnetic pressure $P_m = \frac{H^2}{8\pi}$ along the acceleration channel in steady state mode.

Some key theoretical ideas for resolving these problems of steady-state (or quasi-steady-state) plasma acceleration were proposed by Prof. A.I. Morozov (Kurchatov Institute, Moscow, Russia). He suggested a two-stage acceleration scheme; the formation of a discharge in which the current is mainly carried by ions; the protection of the electrodes by magnetic screening; etc. [5]. A theory for steady-state flows in profiled channels was developed (which it has been used in the next chapter to model plasma flow in the proposed QSPA-SLIDE device).

Experimentally, an ion current in the discharge channel was obtained for the first time at Kharkov, and steady-state acceleration was achieved at the Kharkov and Minsk QSPA devices, where experiment showed ways to influence the potential jumps near the electrode and to keep the discharge current radial for a sufficiently long time to maintain the required gradient of the magnetic pressure [6-12].

3. Plasma flow modelling in the acceleration channel of the *TechnoFusión* QSPA

Calculations of plasma flow and the main plasma parameters were performed in acceleration channels with various different geometries, in order to find an adequate solution for the design of the QSPA-SLIDE plasma source (size, geometry, conceptual components, output plasma characteristics etc.). In doing so, several models for plasma motion in the discharge nozzle were used.

A system of two-fluid magneto-hydrodynamic equations can be written down for a steady-state plasma flow under the reasonable assumption that the electron mass is much smaller than the ion mass:

$$div(nv_i) = 0 \qquad Mn(v_i grad)v_i = grad(p_i) + en(-grad\Phi + \frac{1}{c}[v_i, H])$$

$$div(nv)_e = 0 \qquad 0 = grad(p_e) + en(-grad\Phi + \frac{1}{c}[v_e, H]) \tag{1}$$

$$p_i = p_i(n) \qquad p_e = p_e(n) \qquad rotH = \frac{4\pi e}{c} n(v_i - v_e)$$

If the plasma flow has axial symmetry (and here it shall be only considered this case), the magnetic field has only one component – namely, azimuthal: $H = H_{\Theta}$. In this case, one can obtain the ion and electron flux functions from

$$rnv_r^{i,e} = -\frac{\partial \Psi_{i,e}}{\partial z}, \qquad rnv_z^{i,e} = -\frac{\partial \Psi_{i,e}}{\partial r} \tag{2}$$

Thus, the system of two-fluid magneto-hydrodynamic equations can be written in the following form:

$$\frac{Mv_i^2}{2} + w_i(n) + e\Phi = U_i(\Psi_i)$$

$$\frac{1}{nr}\frac{\partial}{\partial r}\frac{1}{nr}\frac{\partial \Psi_i}{\partial r} + \frac{1}{nr}\frac{\partial}{\partial z}\frac{1}{nr}\frac{\partial \Psi_i}{\partial z} = \frac{1}{M}\left[\frac{\partial U_i}{\partial \Psi_i} - \frac{e}{c}\frac{H}{rn}\right] \tag{3}$$

$$w_e - e\Phi = U_e(\Psi_e), \quad \frac{H}{nr} = -\frac{c}{e}\frac{dU_e}{d\Psi_e}, \quad rH = \frac{4\pi e}{c}(\Psi_i - \Psi_e), \quad w = \int \frac{dp(n)}{n}$$

where $U_{i,e}(\Psi_{i,e})$ is the full energy (kinetic + thermal + potential) of a small "drop" of ions or electrons. In general, $U_{i,e}$ depends on the flux function and can be represented by an arbitrary function $\Psi_{i,e}$ that remains unchanged along the ion or electron trajectory. In reality, the value of $U_{i,e}(\Psi_{i,e})$ is determined by the boundary conditions at the input cross section of the acceleration channel. Provided the electron and ion pressures ($nkT_{e,i}$) may be neglected with respect to the other terms, the energy equations can be written as follows:

$$\frac{Mv_i^2}{2} + e\Phi = U_i(\Psi_i) \qquad -e\Phi = U_e(\Psi_e) \tag{4}$$

These equations are similar to the equations for particle motion. The second equation shows that the electrons are moving along equipotential lines. Another important consequence of this equation is that with metal (equipotential) electrodes, the electrons will not cross these surfaces. Which implies that it is impossible to achieve a regular plasma flow without potential jumps near the electrodes in the acceleration channel. In the case of metal electrodes (equipotential surfaces), the electrical current should be carried by the ions in plasma. The electron drop energy depends on the flux function $U_e(\Psi_e)$ in the following way:

$$U_e(\Psi_e) = U_0 - \kappa(e/c)\Psi_e, \qquad \kappa = const \tag{5}$$

In this case, the following holds in the whole flowing plasma volume:

$$\frac{H}{rn} = \kappa = const \tag{6}$$

This type of plasma flow is known as isomagnetic flow.

The same energy equation can also be written for the ion component

$$U_i(\Psi_i) = U_0 - \kappa(e/c)\Psi_i \quad (7)$$

This type of plasma flow is known as isobernoulli flow. From equation (3) it can be retrieved the Bernoulli integral, i.e., the energy conservation law for ion (or electron) drops:

$$\frac{v^2}{2} + i(\rho) + \frac{H^2}{4\pi\rho} = U = const \text{, where } i(\rho) = \frac{1}{M}(w_i + w_e),\ \rho = nM \quad (8)$$

The system of equations (3) can be solved analytically for two different models corresponding to two different approximations. The first model assumes thin flux tubes, in which the plasma parameters do not change across a flow tube. The second model assumes the channel changes only slowly, so that the acceleration channel is strongly stretched along the axis, and one neglects the proportional part of the equation $\left({v_r}/{v_z} \right)^2 << 1$.

In the thin flux tube model, and taking into account that plasma flow is isomagnetic, the system of equations (3) can be transformed to a system of three algebraic equations for five independent variables (9):

$$rf\rho v \equiv \frac{\dot{m}}{2\pi} = const \text{ ,}$$

$$\frac{H}{r\rho} \equiv \kappa = const \text{ ,} \quad (9)$$

$$\frac{v^2}{2} + i(\rho) + \frac{H^2}{4\pi\rho} \equiv U = const$$

In this system of equations, $f(z)$ is the flux tube width, $r(z)$ the average radius of the flux tube and $\dot{m}$ the mass flow rate. Taking ${v_0^2}/{(2C_{A0}^2)} << 1$ and ${i(\rho)}/{C_{A0}^2} << 1$ at the entrance of the flux tube, the constant in the third equation of (9) will be equal to the Alfvén velocity at the entrance of the flux tube, $U = C_{A0}^2$. With this assumption, one can obtain two asymptotic solutions,.corresponding to two different modes of QSPA operation. The first asymptote corresponds to the pure accelerating mode of operation in which all stored energy is converted into kinetic energy, $\frac{H^2}{4\pi\rho} \rightarrow {v^2}/{2}$, and the plasma enthalpy at the QSPA exit converges to zero. The second asymptote corresponds to the ideal compression mode of operation, in which all magnetic energy is converted to thermal energy, $\frac{H^2}{4\pi\rho} \rightarrow i(\rho)$, and the plasma stream velocity tends to zero.

If one assumes, for the pure accelerating mode of QSPA operation, that the average radius of the flux tube is constant along the axis ($r = r_0 = const$), one can eliminate the magnetic field from (9) and obtain the following system of equations:

$f\rho v = const \quad \left({v^2}/{2} \right) + i(\rho) = const$ and $i(\rho) = i(\rho) + \left({\kappa^2}/{4\pi} \right) r_0^2 \rho$

This system of equations is fully analogous to the system of equations that describes gas flow in a Laval nozzle, except for of the appearance of the signal velocity (in hydrodynamics: sonic velocity). In the dynamic plasma equations, the signal velocity is defined as $c_s^2 = c_T^2 + c_A^2$ where c_T is the thermal velocity and c_A the Alfvén velocity. Thus, the accelerating channel should be profiled. The channel width should decrease from the entry to the critical cross section, where channel width has its minimum, and after the critical cross section the channel width should increase again. At the critical cross section, the local plasma stream velocity will be equal to the local magnetosonic velocity $v_c = c_{sc}$.

The second model deals with a slowly changing plasma flow (the slowly changing acceleration channel model). In this model, terms in the equations like $\partial^2/\partial r^2$ and $\left(\partial/\partial r\right)^2$ can be neglected. Thus, with the assumption $\left(v_r/v_z\right)^2 << 1$, one can transform the system of equations (3) into a set of equations including only the derivative along r. For isobernoulli plasma flow, the ion flux function can be written as:

$$\Psi_i = \frac{r_0^2 v(z)}{2} n_0 \left(1 - \frac{v^2(z)}{v_m^2}\right) \ln \frac{r}{b(z)}$$

(10)

$$n = n_0 \left(\frac{r_0}{r}\right)^2 \left(1 - \frac{v^2(z)}{v_m^2}\right), \qquad \frac{H}{nr} = \frac{H_0}{n_0 r_0}$$

where r_0 is the radius at the entrance of the acceleration channel and b(z) is the radius of central electrode (cathode).

One of the important properties of isobernoulli plasma flow is that the plasma stream velocity does not depend on the radius

$$v_z = \frac{1}{nr}\frac{\partial \Psi_i}{\partial r} = v(z) \tag{11}$$

If the mass flow rate $\dot{m}$ and the discharge current I_d are known, it is possible to calculate the plasma flow velocity in terms of the discharge current:

$$v_m = \Theta\left(\frac{I_d}{c}\right)\frac{1}{\dot{m}}, \quad \Theta = \frac{4}{3\sqrt{3}} \ln \frac{a_*}{b_*} \tag{12}$$

Where a_* and b_* are radius of cathode and anode at the critical cross section, respectively.

Thus, this model allows computing the geometry and the profiles of the electrodes that form the discharge channel. Also, the main plasma parameters, such as the plasma density and the ion and electron velocities can be calculated locally in any region of the acceleration channel. These calculations lead to the proposed geometry and key dimensions of the QSPA-SLIDE source, as will be described below.

4. Basic Specifications for the QSPA device

4.1. General Remarks regarding the QSPA design

In many previous experiments, carried out using small quasi-stationary plasma accelerators and magnetic plasma compressors having discharge currents of up to 200 kA, it was shown that with solid (monolithic) electrodes it is impossible to achieve plasma flow in the acceleration channel without large electric field jumps near the electrodes. The measured plasma stream velocity was much less than predicted by theory.

As can be deduced from the theory of plasma flow in the framework of two-fluid magneto-hydrodynamic models, in profiled acceleration channels the electron component moves along equipotential lines, while the ions cross the equipotential lines. In this case, there are two different ways to organize the plasma flow in the discharge gap.

First – if the discharge current is carried by the electrons, these will need to cross the electrode surface, and to close the electric circuit of the power supply system, so that one has to design non-equipotential electrodes (for example, sectioned electrodes). However, such a design is very complicated technically.

Second – if the discharge current in the plasma flow is carried mainly by the ions (the accelerator operation mode), it can bed use equipotential electrodes but in this mode of operation one needs to convert the current from electron-carried in the power supply system to ion-carried in the plasma flow. In the discharge gap, the ions will move from the anode surface into the plasma flow and thus one must inject ions into the anode region during the discharge in order to maintain the discharge current and so one must protect the cathode surface from this high energy ion bombardment.

Fig. III.2 shows a sketch of the acceleration channel in the operational mode in which the discharge current is carried by ions in the discharge gap.

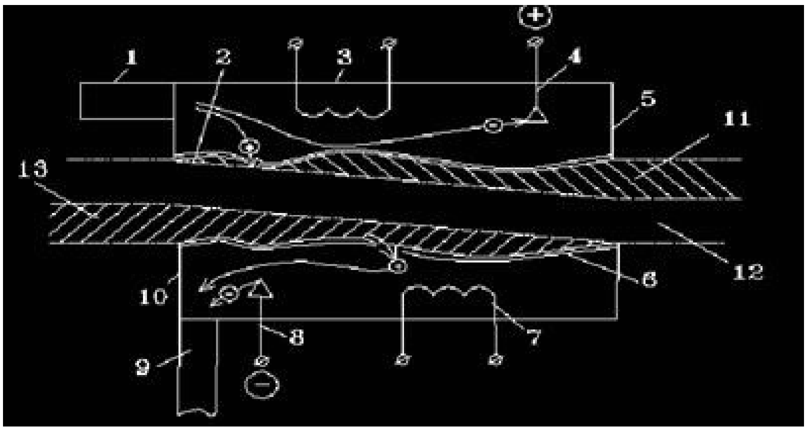

Figure III.2. Scheme of acceleration channel.
1 – ion source in anode volume; 2 – ion emitting surface; 3 – anode magnetic field system; 4 – electron collectors; 5 – anode cover; 6 – cathode collecting surface; 7 – cathode magnetic field system; 8 – electron source in cathode volume; 9 – plasma pump; 10 – cathode cover, it shapes the channel; 11 – near anode flow; 12 – main plasma stream; 13 – near cathode flow.

As can be seen in Fig. III.2, there are three different fluxes in the acceleration channel. The near-anode flux is the ion flux from the anode surface to the acceleration channel, needed to support the discharge current. The core plasma stream is accelerated in the central region. The near-cathode flux is the ion flux from the accelerated plasma stream boundary to the cathode surface, needed to close the electrical current circuit.

Thus there are three key areas involved in achieving long-pulse QSPA operation, avoiding electrode erosion and plasma contamination, and achieving the required plasma parameters (velocity and density). These areas are also important for the transport of plasma in an external B field:

- The input zone, which is the ionization zone;
- The anode zone, that supports the electrical current between electrodes, carried by ions;
- The cathode zone, to protect cathode elements from bombardment by high energy ions;

The conceptual design of the QSPA-SLIDE plasma source, including these 3 zones, is presented in Fig III.3.

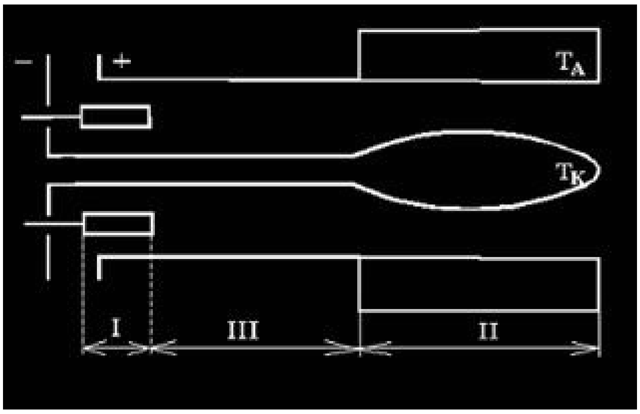

Figure III.3. Conceptual design of the QSPA-SLIDE plasma source: I – input part, II – drift channel, III – main acceleration channel, T_A – anode transformer (anode), T_K – cathode transformer (cathode).

4.2. Design of the main QSPA parts

(a) Entrance section

As mentioned above, the working gas is injected and/or ionized in the entrance section. In previous experiments with MPC and QSPA it was found that the ionization region of the working gas is strongly unstable.

An initial solution to this problem, associated with the ionization zone, is to separate the injection of the working gas, its ionization and its acceleration spatially. In this case, what enters the acceleration channel is not a neutral gas, but a plasma that has been produced previously in several small ionization chambers, operating with a small discharge current.

Another problem that should be taken into account in view of the long-pulse operation of the QSPA device is that the plasma produced by the ionization of gas during later stages of the discharge should move across the magnetic field produced by the discharge current in the main acceleration channel. It is difficult to transport this new plasma across the magnetic field without an additional external force. A theoretical study of isomagnetic plasma flow in the acceleration channel shows that the radial distribution of the plasma density in the entrance section of the QSPA should be proportional to $1/r^2$. As confirmed by many experiments, the necessary $1/r^2$ distribution in the drift channel can be obtained in several ways.

The ionization zone can also be stabilized by, e.g., supersonic gas flows. In this case, the design of the gas tubes should be similar to Laval nozzles. In any case, it is still needed to solve the problem of transporting the plasma from the ionization zone to the acceleration channel, and of creating a radial distribution of plasma density proportional to $1/r^2$.

The simplest way to solve this problem in the QSPA-SLIDE device is to create an additional electromagnetic force in the drift channel, to drive plasma transport towards the main acceleration channel and to shape the radial distribution of the plasma density proportional to $1/r^2$. The proposed scheme is shown in Fig.III.4.

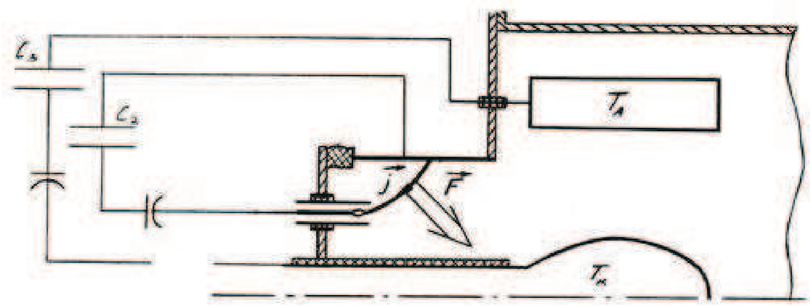

Figure III.4. Scheme of creation of an additional force to drive plasma transport towards the acceleration channel for long-pulse operation of the QSPA-SLIDE device

In this case, an additional current $\vec{j}$ is supplied by an independent power supply system (a capacitor bank), which, together with the existing azimuthal magnetic field, produced by the main discharge current, create an electromagnetic force $\vec{F}$ that transports the plasma towards the acceleration channel and simultaneously focuses the plasma towards the axis.

All three methods described above can be applied to the design of the input section of QSPA-SLIDE. It is possible to apply these methods separately or in combination. For this reason, the design of QSPA-SLIDE contemplates 4 gas tubes (see below) and an additional gas valve in the cathode area. Details of the design are described below in the corresponding chapters.

(b) Anode section

As mentioned above, in the anode the particles carrying the electrical current must be switched from electrons (in the power supply system and cables) to ions (in the plasma), since ions emitted from the anode will carry the discharge current in the acceleration channel.

The simplest design for such an anode transformer is a multi-rod electrode – a anode consisting of rods with an additional outer screen. The volume between the rods and the outer screen is filled by a neutral gas, injected via the entrance section. Our previous experiments show that part of discharge current is distributed in the area exterior to the acceleration channel, by forming a short current path on the outer side of the anode rods. This part of the discharge current sustains the ionization of the neutral gas in the region between the anode rods and outer screen. Thus, a continuous influx of ions to the acceleration channel is provided, the discharge current can be sustained, and electrons will flow to the anode rod surfaces to close the electrical current circuit.

(c) Cathode section

In the operation mode in which the discharge current in the acceleration channel is carried by ions, the plasma ions cross the equipotential lines and move (shift) from the anode surface to the cathode surface. Thus, part of the ions of the accelerated plasma stream should reach the cathode surface and close the current circuit. This implies that energetic ions will reach the cathode surface. Therefore, the electrons in the cathode section of QSPA should neutralize the ion charge and the metal cathode surface should be protected from ion bombardment. As shown in previous experiments with MPC and QSPA in which a monolithic solid cathode was used, the discharge current between the electrodes slides along the surface of the solid cathode, and a high level of cathode erosion accompanied by a significant jump of the electric potential in front of the cathode surface was observed.

Here again the simplest (and effective) design for the cathode section is a multi-rod structure for the profiled area of the cathode. In this way, the neutral gas or cold plasma that is stored inside the cathode volume (under the cathode rods or lamellas) will flow to the discharge area and will produce electrons to close the current circuit. A small part of discharge current, about 20-30 %, will flow to the cathode rods (lamellas), and this part of the discharge current will produce a magnetic field that protects the solid cathode elements from excessive bombardment by high energy ions (by magnetic screening).

The cathode shape, which defines the profile of the acceleration channel, can be computed on the basis of the ideal one-fluid magnetohydrodynamic model, under the assumption that the particle velocity at the entrance of the acceleration channel is close to zero. This assumption is quite reasonable since the neutral gas will arrive at the entrance of the acceleration channel with the thermal velocity, which is much less than the drift velocity or the Alfvén velocity. The profile of the channel width can be written as follows: $h(z)=\frac{2}{3\sqrt{3}}\frac{h^*}{\sqrt{\frac{z}{L}\left(1-\frac{z}{L}\right)}}$, where h^* is the minimum channel width at the critical cross section, and L is the channel length. In this ideal model, the channel width goes to infinity at the entrance and exit sections. But it allows computing the profile of the middle part of the acceleration channel. Assuming the anode diameter is 25 cm (based on: the required plasma parameters, the plasma entrance to the external B-field structure, and the plasma stream diameter due to plasma transport in a strong magnetic field of up to 1 T), the cathode profile was calculated. The results of the 2 types of calculation are presented in Fig. III.5.

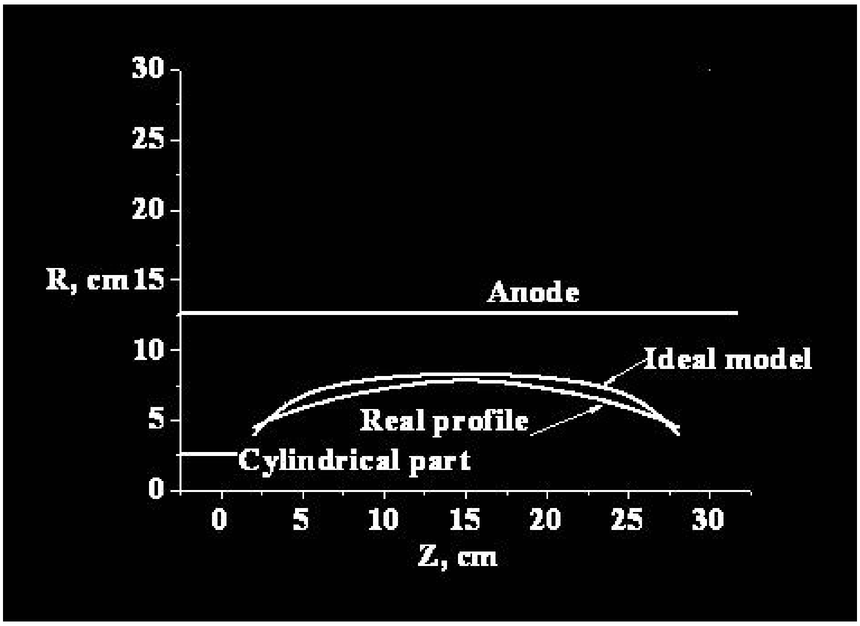

Figure III.5. Results of calculations and the proposed profile of the QSPA-SLIDE acceleration channel.

From this, it has been concluded that the agreement between the calculated cathode profiles on the basis of the ideal model and the real cathode profile proposed for the QSPA-SLIDE device is rather good.

Next, there will be an estimation of some quantities using realistic plasma parameters for the QSPA-SLIDE device, with the proposed profile of the acceleration channel. For example: taking a discharge current of 600-650 kA and an average channel radius of 10 cm; a plasma density at the entrance of the acceleration channel of 10^{15} cm^{-3}, and hydrogen as the working gas, the maximum velocity of the plasma stream at the accelerator output is $v_{\max} = \sqrt{2}C_{A0}$, i.e., approximately (1.1 – 1.3)x10^8 cm/s.

More detailed estimations and results from calculations concerning the dynamics of the plasma stream in the QSPA SLIDE device are provided in Annex 1 of this report.

4.3. General specification of the QSPA device

Figure III.6 shows a block diagram of the QSPA-SLIDE plasma source.

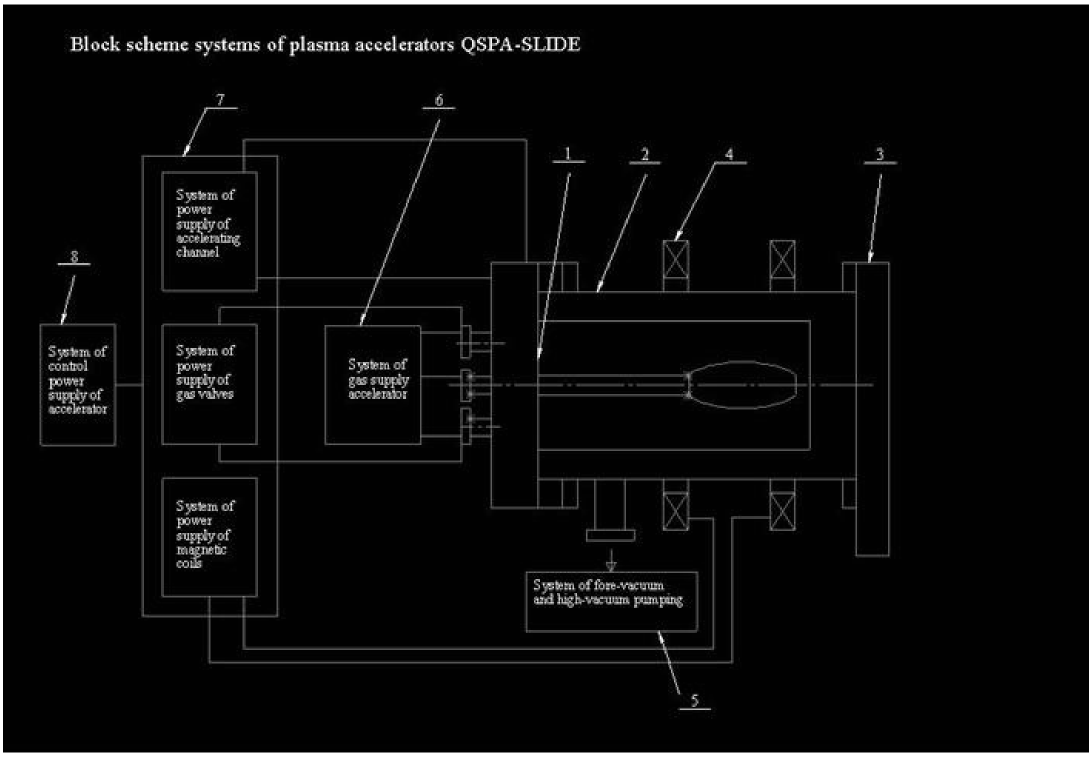

Figure III.6. Block diagram of the QSPA-SLIDE plasma source.
1- plasma accelerator, 2-QSPA vacuum chamber, 3-vacuum gate between QSPA plasma source and L-type vacuum chamber of the combined device, 4- Helmholtz coils for an external magnetic field in the acceleration channel, 5- vacuum pump system of the QSPA chamber, 6- gas supply to electronic valves, 7- power supply of the plasma source and gas valves, coils for the external magnetic field and the main discharge in the accelerator, 8- control system of the power supply.

4.4. Description of QSPA components

The planned experiments to simulate the effect of transient events like ELMs or disruptions on the divertor surfaces of ITER require the generation of plasma streams with parameters similar to that of the SOL plasma flows produced by instabilities [1, 2].

To meet this objective, the recently designed QSPA-SLIDE plasma source will generate plasma streams having the following parameters at the exit of the acceleration channel: electron density 10^{15}-10^{16}cm^{-3}, electron temperature ~ 3÷5 eV, ion impact energy up to 1 keV, plasma stream energy density >2 MJ/m^2, and pulse length ~0.5 ms. After injection of the plasma into the longitudinal magnetic field with axial symmetry and increasing along the path of the plasma stream, the plasma will be magnetized, and transverse compression may elevate the electron temperature to 60 ÷100eV, as has already been achieved in pulsed devices. The energy density of the plasma stream can be varied in a wide range.

The proposed QSPA-SLIDE complex includes the following systems:

- A coaxial plasma accelerator with four electronic valves on the end flange and one valve inside the cathode, and some integrated diagnostics embedded into the structure;
- The QSPA vacuum chamber, with its own pumping system;
- The gas system, gas balloons, pipes etc.

- Two Helmholtz coils for field correction, producing a relatively small external magnetic field of up to 0.1T in the discharge area;
- The power supply system for the QSPA discharge;
- Power supply systems for the electronic valve coils - 5 units in total;
- The power supply of the Helmholtz coil system;
- A synchronization unit;
- A control panel;

(a) Coaxial plasma accelerator

A diagram of the QSPA-SLIDE plasma source is shown in Fig. III.7. Detailed drawings for different parts of the source are still being made. However, the general conceptual design is completed.

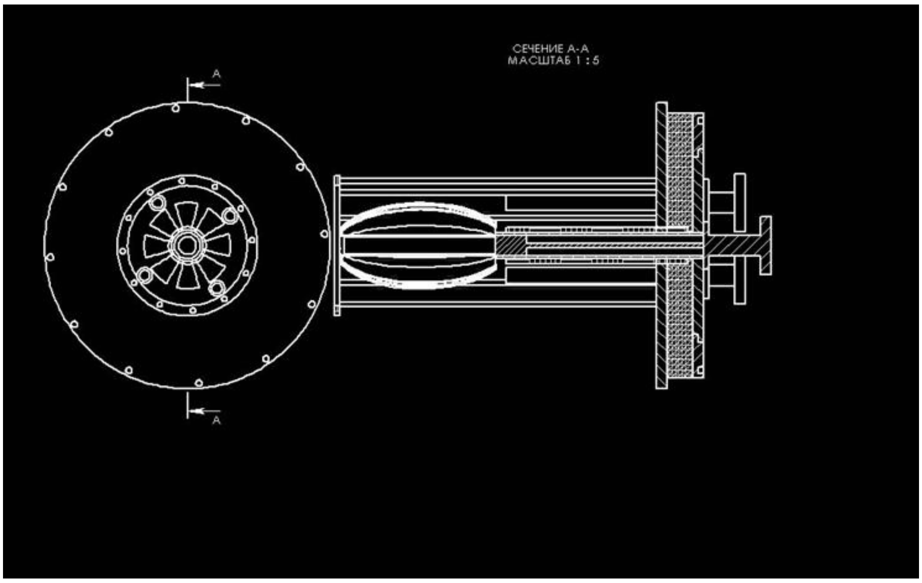

Figure III.7. Drawing of the QSPA-SLIDE plasma source (front and lateral sections)

A front view of the proposed QSPA-SLIDE plasma source is shown in Fig. III.8.

The proposed plasma accelerator consists of two coaxially arranged electrodes: the proposed outer cylindrical rod electrode (anode) (number 2 in Fig. III.8.) consists of a set of rods, forming a “squirrel cage” with an inner diameter of 260 mm and a length of ~700mm. One side of the rod electrode structure is attached to the ring (4), while the other side is fixed to the end flange (3).

The inner electrode (cathode number 1 in Fig. III.8.) consists of a cylindrical tube with a diameter of 50mm and a length of 300mm, and has a lamellar rod structure at the end. This lamellar structure forms the ellipsoid having a maximum diameter of 160 mm at the critical cross-section. The length of the ellipsoid is 300 mm. The other end of the cylindrical tube is welded to the electrode-cathode disk. 5 electro-dynamic valves are mounted on this disk. The anode and cathode flanges are meant function as cable collectors. All electrode components of the plasma accelerator are produced from oxygen-free copper. The total weight of electrode system is about 100 kg.

The anode and cathode electrodes are separated by a plastic isolator disk, to which 5 vacuum-sealed ceramic tubes are attached. One ceramic tube (5), having an inner diameter of 55 mm and a length of 270 mm, is placed in the centre of the isolator disk to maintain the discharge only in the profiled part of the acceleration channel, and to provide a separation of the cathode and anode compatible with the high voltage. Four other tubes (6) with a diameter of 20 mm each and having the same length of 270 mm are situated at 100 mm from the system axis. These tubular isolators protect the cathode and the electronic valves of the gas supply from secondary electrical breakdown during the discharge. This is especially important for the long-pulse operation of the proposed plasma source.

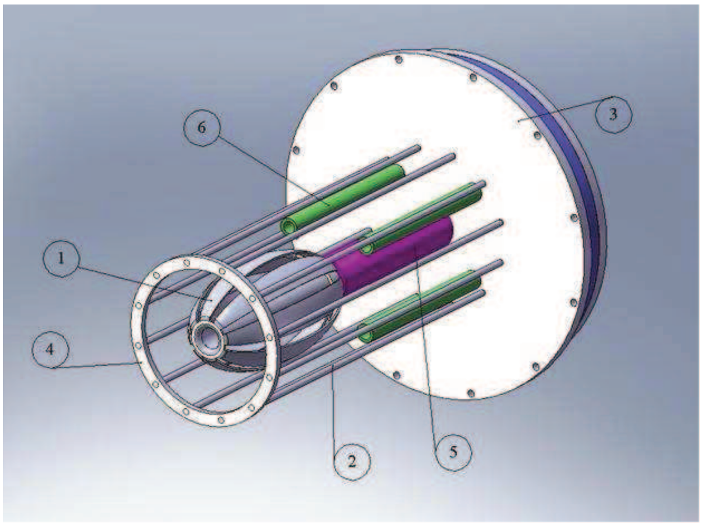

Figure III.8. Front view of the QSPA –SLIDE plasma source. 1-Profiled part of the cathode, 2-anode rods, 3-anode flange, 4-cathode ring, 5-ceramic tube of the cathode, 6- insulator tubes of the gas supply system (the gas valves are inside the tubes).

The electronic valves can inject up to 500 cm^3 of working gas into the discharge gap. Four valves for axial gas supply are located inside the tubes (6). A fifth valve is located inside the cathode tube to provide additional radial injection of gas, directly from the cathode into the discharge zone. The simultaneous operation of several compact gas valves can be useful to achieve more flexibility with regard to the plasma parameters and to decrease electrode erosion with long pulse operation. This flexibility can also be important if it is decided to use other gases than H_2, such as D_2, He or others (or mixtures).

A rear view of the proposed plasma source is shown in Fig. III.9. The gas valves are triggered by pulsed coils (number 8 in Fig. III.9.), mounted on the end flange of the internal electrode (9).

The power supply connections are fed through the flange (3) of the external electrode and flange (9). To prevent high-voltage breakdown between flanges (3) and (9), a face plate isolator (10) will be installed.

A rear view of the QSPA –SLIDE plasma source with an axial cut is presented in Fig. III.10, showing the additional gas valve in the cathode region.

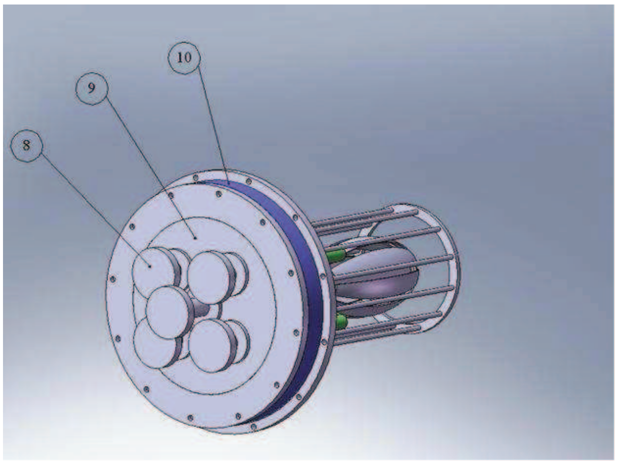

Figure III.9. Rear view drawing of the QSPA –SLIDE plasma source. 8- electro-magnetic coils of the gas valves, 9- the cathode flange, 10- the face plate insulator.

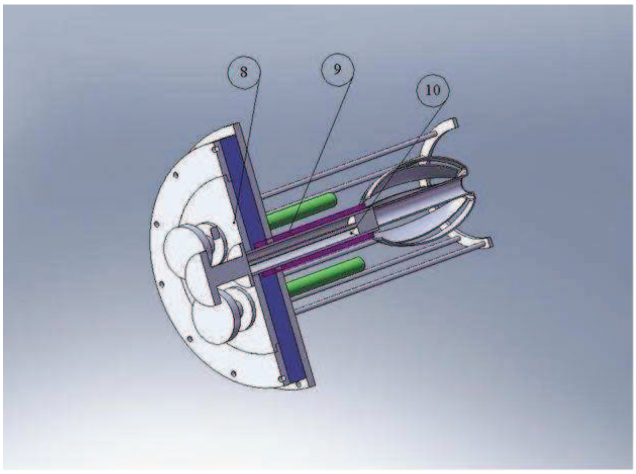

Figure III.10. Rear view with an axial cut of the QSPA –SLIDE plasma source, showing the cathode gas valve. 8- cathode flange, 9- ceramic tube of the cathode, 10- gas valve plate.

(b) QSPA vacuum chamber with pumping system

The cylindrical QSPA vacuum chamber has a length of 800 mm and a diameter of 350 mm. It is made of non-magnetic steel. The plasma accelerator is mounted on one end of the vacuum chamber. The other end is connected to the vacuum vessel of the combined device by means of a sliding shutter with an opening diameter of 350÷360 mm. Four branch tubes with a diameter of 50÷60mm are placed in diametrical opposition on the lateral surface of the vacuum chamber, and provide windows for diagnostic purposes.

The QSPA chamber is pumped through the 180÷200mm diameter branch tube, installed on the lateral surface of the vacuum chamber, with an attached sliding shutter (gate valve). A turbo-molecular pump with an effective pumping speed of up to 600 l/s and a fore-vacuum pump with an effective pumping speed > 5 l/s will create a background pressure in the QSPA chamber of 10^{-6} torr. The crude pumping of the vacuum chamber is performed by a rotary pump with a pumping speed > 5 l/s via the bypass line and the gate valve with an opening diameter of 50÷60 mm, connected to the system pumping branch tube. The estimated cost of the elements of the pumping system is as follows:

- Vacuum installation consisting of a turbo- pump and a fore-pump: - up to 20 TE
- Rotary pump for preliminary pumping : - 4 TE
- Sliding shutter with an opening diameter of 350÷360mm: - up to 1 TE
- Gate valve for rotary pump: up to 0.5 TE

The QSPA vacuum chamber must be attached to one of the ends of the L-type main chamber of the combined *TechoFusión* device. The size and openings of its end flange should be compatible with a sliding shutter, separating the QSPA from the L-type main chamber of the combined *TechoFusión* device

Diagnostics of the QSPA plasma stream, such as calorimeters, electric and magnetic probes, piezo-detectors, spectroscopy, interferometry, etc., should also be provided in order to monitor the operation of the device and the plasma parameters.

(c) Gas supply system

The gas supply system of the QSPA will consist of five bottles with a volume of 5 litters and an operating pressure of up to 15 atmospheres each. Each bottle is connected to one of the five electronic valves by means of a T connector and metal tubes. A high-pressure bottle fitted with a pressure regulator valve allows filling up each of the 5 litter bottles periodically to operational pressure. The gas supply system corresponding to each electronic valve is galvanically isolated from the other gas systems and the ground circuit, so that it will be at high voltage during operation.

(d) Helmholtz coils

The proposed design contemplates Helmholtz coils inside the vacuum chamber to stabilize the discharge in the acceleration channel. Additionally, these Helmholtz coils allow correcting the geometry of the axial magnetic field at the exit of the plasma accelerator. Each magnetic coil has a diameter of 600 mm and a width of 60 mm, and has a low inductance. The magnitude of the magnetic field created by the Helmholtz coils must be about 0.1 of the internal (proper) magnetic field produced by the accelerator discharge current. The pulse shape should match the waveform of the discharge current and have the same duration.

The plasma flow in the presence of both a weak longitudinal B-field, below 0.1 T, and the proper azimuthal B-field of about 1 T is calculated using a simplified model. Any rotation of the plasma column will add stability at the point where the plasma stream enters the transportation chamber.

(e) QSPA Plasma Transportation in an External B-field

The QSPA will be placed in a region with a field of 0.1T (Helmholtz coils), so it is convenient that the B-field increases slowly from 0.1 T to 1T along the plasma path for further transportation of the plasma stream.

The B-field should only reach 1 T at the last 2 coils. At the first coils (close to the QSPA) the field should be lower, i.e. (0.1-0.5) T, to avoid large plasma losses at the entrance to the magnetic system. The QSPA discharge will be perturbed by external fields of 1T in the discharge area.

Even a calculation of a single iteration yields a strong B-field ripple in the combined *TechoFusión* device. Thus, near the QSPA output the coils should be close to each other (either using wider coils or adding additional coils) to provide a more favorable scenario for plasma compression and to decrease the diameter of the plasma stream.

The entry of the QSPA plasma into the magnetic field system of the combined *TechoFusión* device can be controlled by varying the electric current in both the Helmholtz coils and the entrance coils of the L-shaped chamber. Also, modifications to the coil positions, their size, and the distance between the Helmholtz coils and the entrance coils of the L-shaped chamber are considered. Corresponding numerical simulations have been performed. As an example of such calculations, the result of varying currents and coil displacements is shown in Fig. III.11 for a maximal field of 2 T and a diameter of the chamber coils of 25 cm. Final calculations will be performed after the detailed design of the L-shaped chamber has been established.

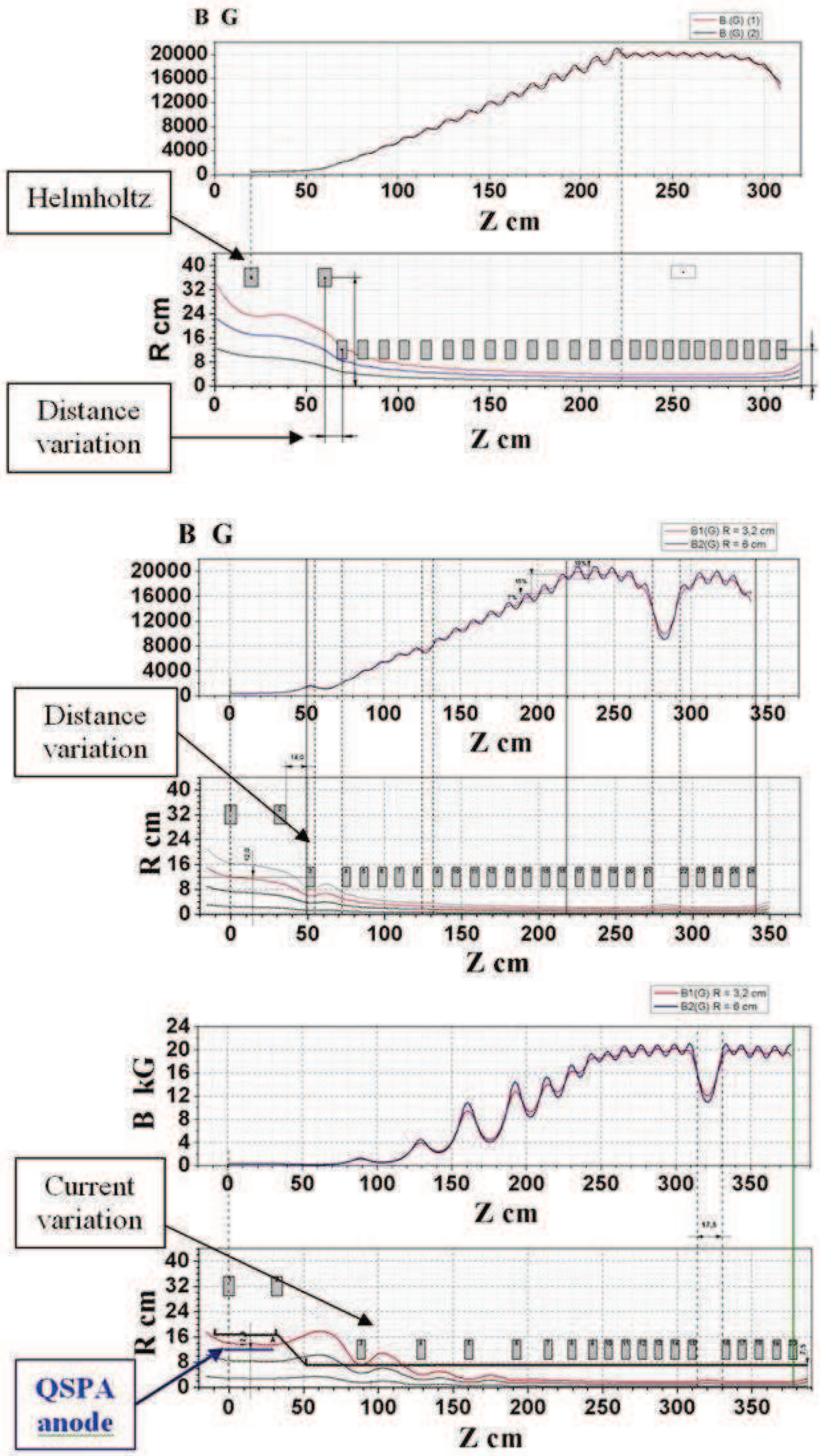

Figure III.11. Example showing the effect of varying currents and coil displacements.

(f) Power supply system of the QSPA discharge

The power supply system of the accelerator consists of a high-voltage device to charge the capacitor banks to the operating voltage, a capacitor bank for energy storage with a total capacity of 0.01F, and a set of switch tubes (switchers) to connect the energy storage capacitor bank to the plasma accelerator. A block diagram of the power supply for the QSPA-SLIDE plasma accelerator is shown in Fig III.12.

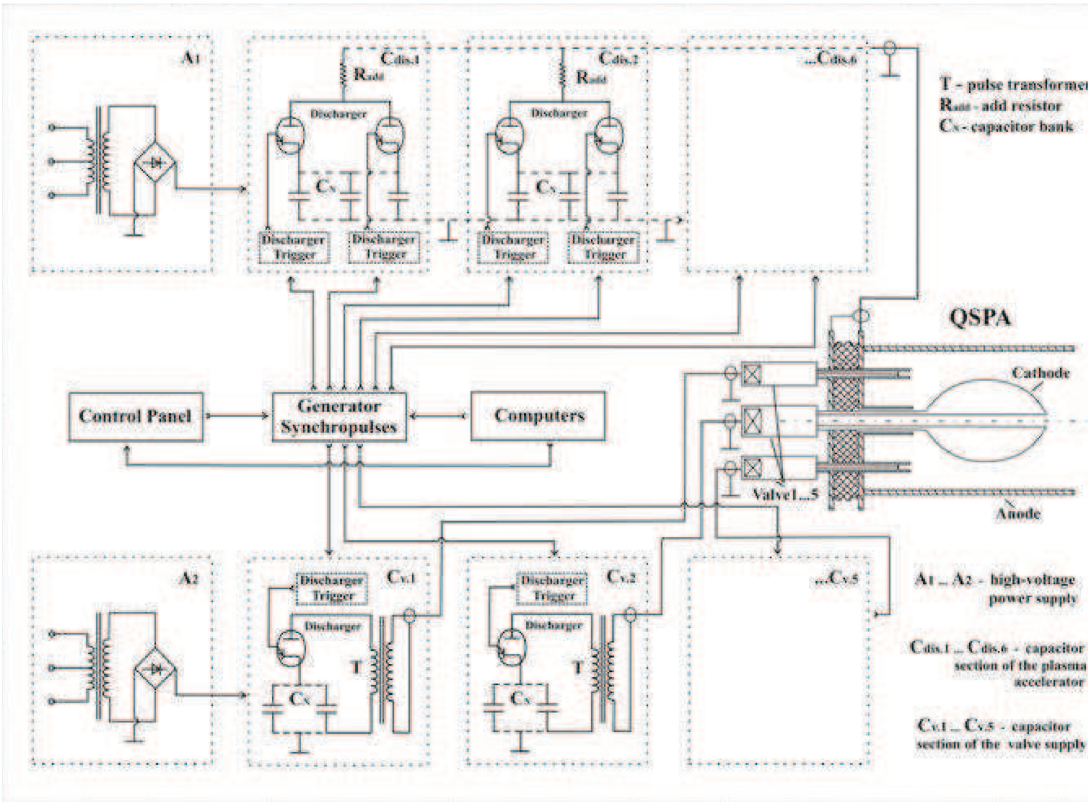

Fig.III.12. Block diagram of the QSPA-SLIDE power supply

The high voltage power supply for charging the capacitors must be capable of regulating the operating voltage up to 20 kV and provide a charging rate of 10 kJ/s, with either positive or negative output polarity, for 3÷3.5 min. “General Atomics Energy Products” designs and manufactures Standard and Custom high voltage, high power AC/DC switching power supplies; for example: the CCS10025P1C module with the following parameters:

- output voltage: 0-25 kV;
- output current: 0.8A;
- power rating: 10 kJ/s;
- size: 222 mm height x 482 mm width x 508mm depth;
- weight: 29 kg.

Such a power supply satisfies our requirements and can be used for the QSPA-SLIDE device.

Custom designed or home-made power supply systems can also be considered.

The capacitor battery should consist of six sections, each with a different capacity.

The calculations that have been performed suggest the following solution for the QSPA-SLIDE power supply system: the first section of the capacitor battery must have a capacity of 0.0034 F, the second 0.0022 F, the third and fourth 0.00167 F each, the fifth and sixth 0.00042 F. Each section is composed of e.g. Maxwell energy storage high voltage capacitors with a capacity of 206 µF, and an operating voltage of 22kV (for instance, series C part number 32349). The casing of each capacitor has a size of 305×407×696 mm and a weight of 145.2 kg. The total area occupied by the capacitor battery will then amount to 6.5 m^2. The cost of a capacitor is about 2,200$. The overall cost of the capacitor bank is estimated to be below 103.5 thousand $.

The operation of the capacitor bank will be non-periodic. The sections should be switched on in series with a preset time delay, allowing the shaping of the current waveform in the plasma accelerator, with a maximum current of 700kA at the capacitor bank voltage of 20kV and pulse duration of 0.5ms.

Based on the electro-technical characteristics and the parameters of the discharge circuit, numerical calculations were performed to study different scenarios for the discharge of capacitor sections, with the aim of controlling the pulse shape of the discharge current and the voltage. An example of such calculations for the current waveform and voltage is shown in Fig. III.13. The effect of switching the various sections on the discharge current can be observed. After selecting an appropriate scenario, the discharge current can be kept rather constant during 0.5 ms.

Alternative solutions exist for the parameters of the capacitor battery, depending on the available capacitors.

Note also that the capacitor battery can be designed with several segments, which allows varying the discharge duration (for example, either 0.5 ms or 0.25 ms by switching on or off a segment).

The planned setup contemplates switch tubes (switchers) in the discharge circuit of the plasma accelerator in order to control the connection of the capacitor bank energy to the plasma accelerator. Each capacitor section has one or a few switch tubes, allowing it to be switched on independently from the other sections. The choice of switch tube depends on the voltage, the commutated current, the charge and the pulse duration. The T-150 Spark Gap Switch and TG-1292 Trigger Generator produced by **"L-3 Communications Pulse Sciences"** are suitable for this purpose. Nevertheless, other solutions can be considered.

The T-150 Spark Gap Switch has the following parameters: operating voltage: 20-40 kV; peak current: 300 kA; charge transfer: 120 coulomb per pulse; gas flow rate > 30 scf/hr. In view of the technical characteristics of the T-150 Spark Gap Switch, it is convenient to use twelve T-150 Spark Gap Switches to commutate the capacitor bank. They will be mounted between the sections in following sequence: in threes for the first and second sections, in twos for the third and fourth sections, and in ones for the fifth and sixth sections. The cost of a T-150 unit is approximately 14.5 thousand USD.

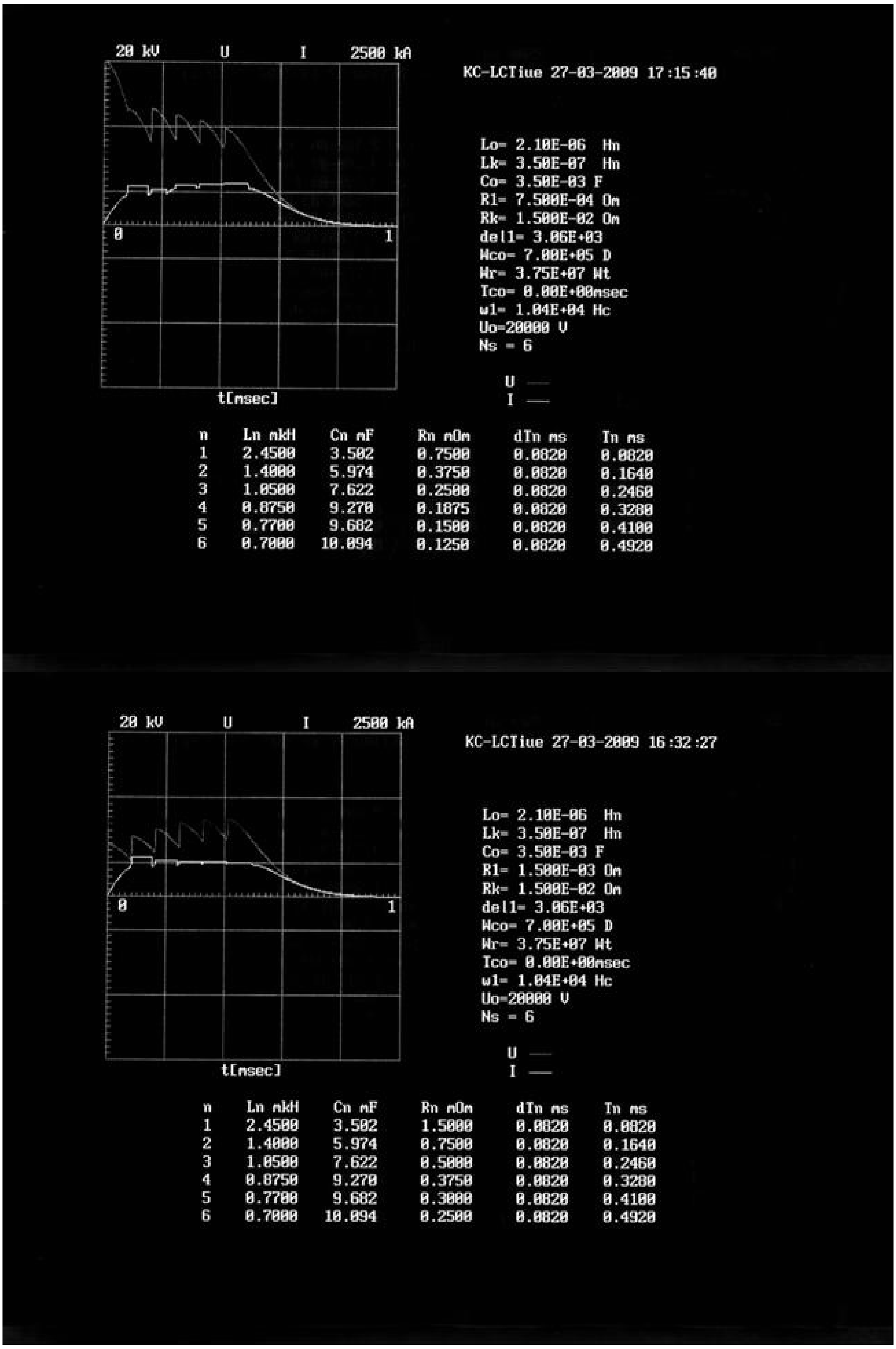

Figure III.13. Example of calculation results using different pulse shapes for the discharge current and the discharge voltage in QSPA-SLIDE.

(g) Power supply systems for the coils of the electronic valves

The design of the QSPA contemplates five electronic valves to control the injection of working gas (e.g. hydrogen, helium, deuterium, or various mixtures, including Xenon) into the discharge region of the plasma accelerator. Due to the interaction between the magnetic fields produced by an inductive current in the valve disk and the magnetic coil of the valve, the **electronic** valve opens and injects gas. The power for the magnetic coil of the valve is supplied by a capacitor bank with a capacity of 500 µF and an operating voltage of up to 5 kV each. The capacitor bank consists of 5 capacitors with a capacity of 100 µF and a nominal voltage of 5 kV (for example type IK41-I7).

An ignitron switcher (IRT-6) is used to commutate the discharge current in the valve circuit. The discharge is periodic. All electrical circuits of the electronic valves are galvanically isolated from each other and from the accelerator electrodes. A high voltage capacitor power supply is used to charge each capacitor bank and must be able to regulate the voltage from 0.5 kV to 5 kV and provide a charge time of about 3 min at a voltage of 5kV (the nominal power is about 35J/s).

(h) Power supply of the Helmholtz coils

The power of the Helmholtz coils is also supplied by a capacitor bank. The required magnetic field in the Helmholtz coils is produced by 67 kiloampere-turns. For coils with 32 turns, the capacity of the battery is 1600 µF at a voltage of 3 kV. The proposed high voltage power supply for the capacitor must be able to regulate the voltage from 0.1 kV to 3 kV and have a nominal power rating of 40 J/s.

(i) Synchronization unit

A synchronization unit (pulse generator) is needed to provide synchronised triggers to switch the capacitor banks of the Helmholtz coils, the gas valves and the main discharge of the plasma accelerator with appropriate time delays. Each channel of the synchronization unit triggers one discharge with an adjustable time delay. In addition, a few triggering channels are needed for the oscilloscopes and the computer ADCs. The pulse height and duration will be determined in the detailed design phase.

It should be noted that industrial solutions are available for the synchronization unit.

(j) Control panel

The control panel includes the following control blocks:

- A control block for the activation and deactivation of the elements of the vacuum system;
- A control block for the power supply for charging the discharge capacitor bank. It controls the activation and deactivation of the power supply, it regulates the charge level of the capacitor bank, and it generates a signal indicating the readiness of the capacitor bank for operation.
- A control block for the coil valves, and the power supply for charging its capacitor banks. It fulfils similar functions;
- An interface board for connection to a computer;

- Voltmeters for visual inspection of the charge (voltage) of the capacitor banks;
- A start signal that is sent to the input of the synchronization block after receiving acknowledgement of readiness from the capacitor banks;
- An interlock system controlling the electromagnetic contactor, short-circuiting the capacitor banks and the high-speed electric protection;
- In addition to conventional tasks, the control system should be able to monitor and disconnect any part of the power supply while keeping the rest of the device operational. The control panel should offer both a manual and a programmed mode of operation. The elements of the control panel are not very costly and will be defined in detail as the engineering design of the circuits progresses.

5. Conclusions

A general design has been made for the QSPA-SLIDE plasma source for the *TechoFusión* facility in Madrid. Profiled electrode rods were chosen for its basic design. The external electrode of the plasma source will have a diameter of 260 mm and a length of ~700 mm. The profiled part of the internal electrode will have an ellipsoidal shape with a maximum diameter of 160 mm at the critical cross-section. The length of the ellipsoid is 300 mm.

The plasma flow was calculated for the chosen accelerator geometry on the basis of an MHD model in 2 different approximations.

Several methods were considered for the gas feed. A combination of gas supply at the end and gas injection in the cathode region was chosen. Electronic valves are able to feed up to 500cm^3 of working gas into the discharge gap. The design contemplates four valves for axial gas supply. A fifth valve is located inside the cathode tube to provide additional radial gas injection from the cathode directly into the discharge zone.

The application of small external magnetic fields in the discharge area (Helmholtz coils) was considered. It was concluded that a longitudinal magnetic field of 0.1.B_{int} improves the stability of the plasma stream and the transport of plasma into the external B-field of the L-shaped vacuum chamber of the *TechoFusión* facility.

A basic specification of the QSPA-SLIDE device was made. The key parameters of various QSPA systems were determined.

Estimates were made of the electro-technical specifications of the power supply systems for the different elements of the QSPA-SLIDE device

Globally, the QSPA-SLIDE device designed here is smaller and simpler (but more effective and powerful) than the existing QSPA Kh-50 device. Compared to QSPA-T, the designed facility is somewhat more complicated, but qualitatively enhanced in several respects, which will provide some important advantages: the possibility to transport plasma into a strong B-field, a much lower level of impurities, higher particle energies, etc.

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ANNEX TO APPENDIX III

Analysis of plasma flow in the SCC model for the QSPA-SLIDE geometry

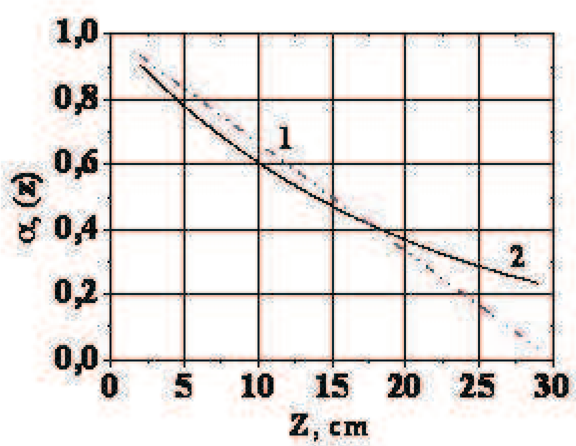
Some properties of plasma flow in the acceleration channel were analyzed with the Slowly Changing Channel (SCC) model. The main assumption in this model is that the acceleration channel varies slowly along the axis, so that $\left(v_r / v_z \right)^2 << 1$. This model is appropriate for the description of the main central part of the acceleration channel, but not for the entry section, where large gradients in plasma stream velocity exist, or the exit section, where dissipative processes play a large role. Here, it is assumed that the thermal energy of the particles is much less than the kinetic energy $W << \mathrm{E}_i$, and that the exchange parameter $\xi = \frac{I_d}{I_{\dot{m}}} << 1$, where I_d is the discharge current and $I_{\dot{m}}$ the mass flow rate in electric current units. The latter assumption means that the electron and ion trajectories are rather similar to one another. It has been stressed that in this model, the discharge current between the electrodes flows in the radial direction only, and the plasma stream velocity does not depend on the radius.

Considering the above, the ion flux function can be written:

$$\Psi_i(r,z) = \sqrt{2} a_*^2 n_{0*} C_{A0} \alpha(z) \sqrt{(1-\alpha(z))} \ln\left(\frac{r}{b(z)} \right)$$

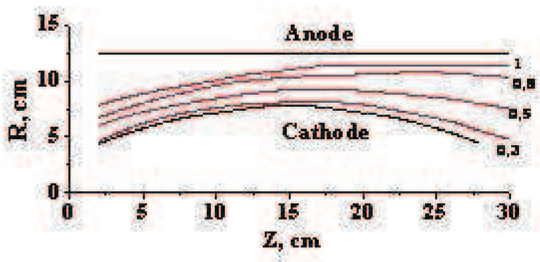
Where $\Psi_i(r,z)$ is the ion flux function; a_* the average radius at the entry section of the acceleration channel; n_{0*} the plasma density at this point; C_{A0} the Alfvén velocity at this point; $\alpha(z)$ the dependence of the discharge current on the channel axis; $b(z)$ the cathode radius (assuming that the anode is a cylinder) and r the radius.

Thus, the ion flux function (i.e., a function such that $\Psi_i = const$ corresponds to ion trajectories) depends on the distribution of the discharge current along the channel axis $\alpha(z)$ and on the channel profile, namely the cathode profile $b(z)$, since the anode is cylindrical. Two different types of dependency of the discharge current on z were considered in these calculations. The first is linear dependence. This case is simple, but produces a value of the discharge current at the accelerator exit that is close to zero. In recent experiments, a part of the discharge current, typically about 25-30%, flows in the plasma stream outside the acceleration channel. Thus, another dependence was used to estimate the ion flux function, taking into account that about 25% of the total discharge current flows outside the acceleration channel.

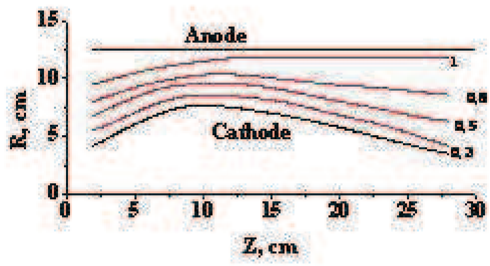


Two dependencies of $\alpha(z)$.

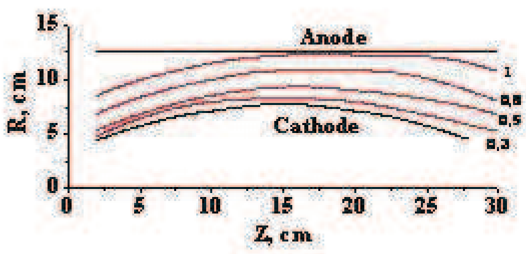
Ion flux functions were calculated for two different discharge current distributions along the axis and for two acceleration channel profiles. The results of these calculations are presented in the figure below.



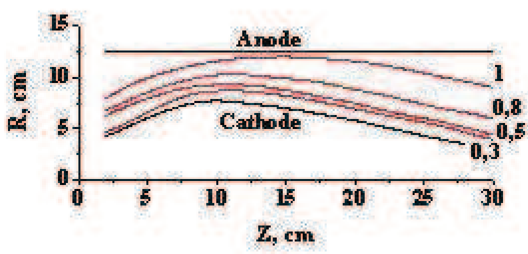
Ion flux function for dependence $\alpha(z)$ - 1.



Ion flux function for dependence $\alpha(z)$ - 1.



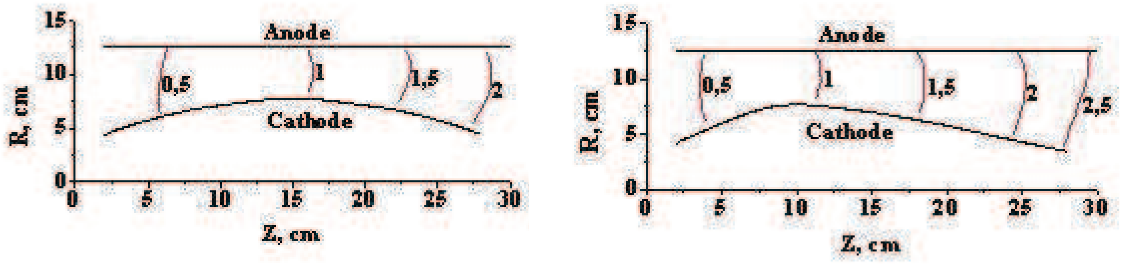
Ion flux function for dependence $\alpha(z)$ - 2.



Ion flux function for dependence $\alpha(z)$ - 2.

These figures show that about (70-80)% of total plasma stream flows outside the acceleration channel, inside a cylinder with diameter of 16-17 cm.

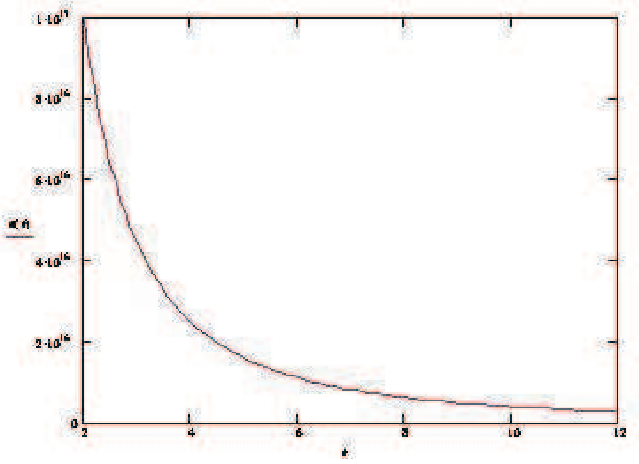
Based on the ideal SCC model, the ratios of the ion velocity v_i to the local signal velocity $v_s = \sqrt{v_A^2 + v_{Ti}^2}$ were calculated. Taking into account that the thermal energy of the particles is much less than their kinetic energy, the local signal velocity is equal to the local Alfvén velocity: $v_s \approx v_A$. Calculated ratios, i.e., lines of equal levels of v_i / v_A, are shown in the figure below for two different channel profiles and a linear dependence of the discharge current along the axis.



Lines of equal values of v_i / v_A.

These figures show that the plasma stream is accelerated along the channel, while the achieved velocity is about (2-2.5) times the local Alfvén velocity at the channel exit.

Based on the SCC model, the value of the plasma density at the entrance of the acceleration channel and its radial distribution was estimated. It is seen that the total mass flow rate equals $\dot{N} = 2\pi\Psi_i^{\max}$. It has been expected to reach a maximum discharge current in the acceleration channel of about 600 kA, and an exchange rate of $\xi = 0.1$. In this case, the total mass flow rate should be $I_{\dot{m}} \approx 3.6\times10^{25} s^{-1}$ and $\Psi_i^{\max} = 6\times10^{24} s^{-1}$. The average radius at the entrance of the acceleration channel is $r = 10cm$. Thus, the plasma density at $r = 10cm$ should be $n \approx 5\times10^{15} cm^{-3}$, and its radial distribution should look like what is shown in the figure.



Radial distribution of the plasma stream density et the entrance of the acceleration channel of QSPA SLIDE.

Two different methods exist to obtain such a radial distribution of plasma density. The first is to inject some neutral gas from the cathode into the acceleration channel at the entrance of the channel. The second is to create an electromagnetic force at the entrance of acceleration channel that pushes the plasma towards the cathode. Both methods can be applied in the QSPA facility.

The maximum exit velocity can be calculated based on the calculations above. For a discharge current of $I_d = 600kA$ and plasma stream densities at the entrance cross-section of $n = 5\times10^{15} cm^{-3}$, the maximum velocity should be $v_{\max} = 1.1\times10^{8} cm/s$. It has been emphasized that this value of the plasma stream velocity requires that the discharge current between the electrodes flows only in the radial direction.