

Michel Moisan

Curriculum vitae

May 2023

Michel Moisan was born in Montréal (Québec) on May first 1942.

Training

- 8 years of "*Classical*" studies (*comprising Latin, Ancient Greek and Philosophy*) (Collège André Grasset, Montréal) completed in 1961 in Section C (science-engineering) with highest honors *Summa cum laude*.
- *Bachelor of Physics* (1961-1964) and Master of Physics (Plasma physics specialty) (1964-1966) at the Université de Montréal.
- *Doctorat d'État* (State Doctorate) also called *Doctor of Science* (1966-1971) at the Université Paris-Sud (Campus d'Orsay), now known as Université Paris-XI. Title of the thesis: Ionic instabilities in the presence of an intense electromagnetic field. Defense of the thesis with the congratulations of the jury (external examiners: Frederick W. Crawford, Electrical engineering, Stanford University; Paul Vandenplas, École royale militaire, Bruxelles).
- *Post-doctoral internship* (January-October 1972) at the invitation of the academician L.A. Artsimovitch (head of plasma physics in the USSR) for having demonstrated experimentally the validity of a theoretical model developed by scientists (Aliev and Silin) of the Institute of Physics PN Lebedev (Moscow), the most famous physics center in the USSR at that time. According to the administration of the Academy of Sciences, at that time I was their youngest guest as a visiting scientist.

Fellowships

- MSc, Doctorate and Postdoctoral Fellowships (NRC Scholarships, now NSERC).
- Additional Doctorate Fellowship: Québec Ministry of Education Fellow, on an honorary basis (non-cumulative) during the period of validity of the NRC Fellowship, but once this period ended, full-time Fellow (1969-1970). Also: Technical Cooperation Fellowship (France) (1966-1971).

Note on the NSERC Postdoctoral Fellowship: it was canceled without any written notice, probably on the grounds of not having responded to an invitation to meet with the RCMP (Canadian Federal Police) some time before my departure for the USSR. (Partial) funding of the stay in USSR by Canadian External Affairs as part of their Agreement with the USSR Academy of Sciences, and by the USSR Academy of Sciences.

Academic positions

- Research Associate: Plasma Physics Group, Université de Montréal (October 1972-December 1975).
- Professor: Département de physique, Université de Montréal. Rank: Assistant professor (January 1976-1979), Associate professor (1979-1985), Full professor (1985-2015).
- Professor Emeritus (Physics) at the Université de Montréal (nomination April 2015 upon retirement).
- Co-founder (2008) with Jacques Pelletier (Grenoble) of LITAP, International Laboratory for Plasma Technologies and Applications, now an International Research Group (GDRI).

Sabbatical leaves

- IBM TJ Watson research center (Yorktown Heights, NY): 4 months in 1985.
- Centre National d'Études des Télécommunications (CNET) (National Center for Telecommunication Studies), Grenoble: 6 months on 1985-1986.
- Other internship CNET (1997) with (temporary) appointment as Professor of the first class of the Universities.

Awards

- Prix Adrien-Pouliot 2005 (France-Quebec Scientific Collaboration), granted by the Association francophone pour le savoir (Acfas) and the Consulat Général de France au Québec.
- Innovation Award 2017 conferred by the Division of Plasma Physics of the European Physics Association (EPS), received during their annual meeting in Belfast (June 2017).

Short citation: "For pioneering contributions to the development and understanding of microwave plasma sources and their applications to materials processing, healthcare and environmental protection".

Full Citation (nominator Professor David B. Graves, UC at Berkeley): "Professor Moisan has made numerous, profound contributions to plasma physics and especially to the applications of plasma for a variety of commercial and industrial applications. He was the lead inventor appearing on the 1974 patent application disclosing the 'surfatron' and 'surfaguide' electromagnetic field applicators. These devices have been truly enabling for many plasma applications. They are widely used throughout the world for sustaining stable and reproducible plasma columns under a large range of operating conditions. The plasma discharge using these devices is conveniently achieved in dielectric tubing, allowing flowing gases to be utilized. The applied frequency ranges from 150 kHz to 40 GHz with discharge tube diameters from 1 mm to 300 mm radius. Plasma can be sustained with gas pressure as low as 1 mTorr (with electron cyclotron resonance (ECR) operation) to at least 10 times atmospheric pressure. It should be stressed that establishing and maintaining stable plasma under such a wide range of conditions is not possible with any other existing plasma sources."

These devices have enabled fundamental studies into the structure and dynamics of RF and microwave plasmas to a degree heretofore unattained. An especially powerful property is that the EM-field configuration remains the same from 150 kHz to a few GHz, allowing specific plasma studies of the effects of field frequency on plasma parameters.

However, the value of these devices is even more impressive for industrial and many other practical applications. Hundreds of surfatrons are being utilized worldwide in industrial and research labs, and this design is now so widely accepted and integrated into the plasma community that publications no longer refer to its inventors. Among many others that could be cited, the following abbreviated list identifies some examples of practical and novel use: 1) robust, reliable secondary-ion mass spectroscopy (SIMS) in a French-Soviet spacecraft around Phobos, a Mars satellite; 2) efficient, powerful, low damage, room temperature surface sterilization; 3) efficient abatement effluent of difficult-to-treat global warming gases (perfluorocarbons and hydrocarbons) in chemical plants and semiconductor fabs; and 4) highly efficient and powerful purification of Kr and Xe gases obtained from cryogenic distillation in industrial chemical plants. Indeed, many different types of surface-wave launchers and a great variety of applications were developed over the years by the team of Professor

Moisan as well as by many other teams throughout the world. The gas abatement applications were patented, under Prof. Moisan's name, by the French multinational company Air Liquide".

- Chevalier dans l'Ordre des Palmes académiques de la République Française (Knight in the Order of Academic Palms of the French Republic) (decree of 11 January 2017) for scientific collaboration with France. Medal bestowed on December 7, 2017 by the Consul General of France in Montreal, Mrs. Catherine Feuillet, in the presence of UdeM Rector professor Breton.

Other activities

Scientific consulting (details under Scientific collaboration with companies)

Westinghouse (Pittsburgh, USA) 1980-1982

Standard Oil of Ohio (Cleveland, USA) 1982-1984

Singer Corp. (Kearfott gyrolaser guidance division, USA) 1984

IBM (Central Lab., Yorktown Heights, USA) 1984-1988

ICI (Manchester, UK) 1985-1988

Xerox (Webster Research Center, USA) 1988-1989

Fusion System (Rockville, MD, USA) 1992-1994

Technologies MPB (Montréal) 1993-1994

Air Liquide (France) 1994-2005

Peintures (*Paints*) Prolux (Montréal) 1997

Getinge, Infection Control division (Sweden) 2013-2014

Cell Foods (*Spices*) (Montréal) 2014)

Member of scientific committees

- Organizing Committee, IEEE conference on plasma science (Montréal, 1979)

- Program Committee and co-organizer, First conference on surface waves in plasmas (Blagoevgrad, Bulgaria, 1981)

- International Committee and co-organizer of Second international conference on surface waves in plasmas and solids (Ohrid, Yougoslavia, 1985)

- Member of the executive committee, Gaseous electronics conference (GEC) (1992-1994), and organizer (secretary) of the 46th GEC (Montréal, 1993)

- Co-director (with C M Ferreira) of Summer School (NATO Advanced Study Institute) in Vimeiro, Portugal, 1993.

- Member of the Plasma Chemistry sub-committee, International Union of Pure and Applied Chemistry (IUPAC), 1994-1997

- International scientific committee of the 3rd international workshop on microwave discharges (Fontevraud, France 1997)

- Advisor committee of NATO Summer School (Advanced Study Institute) in Sozopol, Bulgaria, 1998
- Advisor committee (Comite asesor internacional) of the Jornadas Sam'98 Iberomet V (Rosario, Argentina)
- Advisory Committee of CIP (Conférence Internationale Plasmas) 99 and 01 (Antibes-Juan-les-Pins) of the French Vacuum Society (SFV) 1999, 2001
- International Scientific Committee of the 4th international workshop on microwave discharges (Moscow, September 2000)
- International Committee of ECASIA 01 (European Conference on Surface Applications and Interface Analysis, Avignon, France, 2001)
- Chair of (new) ECRIN committee of the Pisa Club on plasma sterilization, a French company-university association located in Paris (2002-2003)
- President of the CIP International Committee 2003 (14th International Colloquium on plasma processes), June 2003, Antibes (France).
- Member of the International Scientific Committee of 5th Int. Workshop on Microwave Discharges: fundamentals and applications, Zinnowitz (Greifswald, Germany), July 2003
- President of the International Committee of the CIP 2005 (15th Int. Colloquium on plasma processes), June 2005, Grenoble (France).
- Member of the multidisciplinary evaluation committee to examine the Team Research Project (FQRNT) program (a Québec funding agency), Fiscal Year 2006-2007.
- Member of the International Scientific Committee of 6th Int. Workshop on Microwave Discharges: fundamentals and applications, Zvenigorod (Russia), September 2006
- Member of the International Committee of the CIP 2007 (16th Int. Colloquium on plasma processes), June 2007, Toulouse (France).
- Member of the CIP International Committee 2009 (17th Int. Colloquium on plasma processes), June 2009, Marseille (France).
- Member of the International Scientific Committee 7th Int. Workshop on Microwave Discharges (MD-7): fundamentals and applications, Hamamatsu (Japan), September 2009.
- Member of the editorial board of the journal of Plasma Medicine (since 2011).
- Member of the International Scientific Committee of 9th Int. Workshop on Microwave Discharges (MD-9): fundamentals and applications, Córdoba, Andalusia (Spain), September 2015.
- Member of the International Scientific Committee of 10th Int. Workshop on Microwave Discharges (MD-10): fundamentals and applications, Zvenigorod (Russia), September 2018.

Member of peer committees

- President of the Research Committee of the Université de Montréal and its affiliated schools (1980-1983), elected by the Assemblée Universitaire. Université de Montréal et ses Écoles affiliées (HEC, Poly Montréal) are French-speaking institutions with more than 70 000 students.
- NSERC (Canada's research agency: Committee 29 (General Physics), 1992-1995).
- FCAR (Québec's research agency: Young researchers 1991-1992, Team 1999-2000).

Academic, industrial and commercial achievements

- Lead inventor of the surfatron and surfaguide, EM field applicators that allow to achieve producing plasmas with RF and microwaves fields. Available from the French company Sairem: 99 surfatrons had been sold till 2017.
- Director (1983-2008) of the Groupe de physique des plasmas (Plasma Physics Group) at the Université de Montréal (UdeM) who developed an ecological purification technique (to remove hydrocarbons and fluorinated compounds) from rare gases such as Krypton and Xenon obtained by cryogenic distillation of air (Industrial respondent: DGR (Rare Gases Division) of Air Liquide (France)). Production Center of Moissy-Cramayel, France and German production center of the Air Liquide Company.
- The UdeM plasma team also developed a technique for the environmentally friendly elimination of greenhouse gases (for example, CF₄, SF₆) used in the manufacture of microelectronic chips. UPAS system (Universal Plasma Abatement System), marketed by Air Liquide. (Air Liquide Electronic System (ALES) industrial respondent) in collaboration with the Claude-Delorme (main) Research Center (CRCD) of Air Liquide (AL, France).¹
- Scientific Director of the UdeM plasma team (with the Laboratoire de contrôle des infections, a microbiology group) which came up with a new process for sterilizing low-temperature medical devices (<70° C). Research and Development contract, signed through our valuation company (Univvalor) and with funding 2013-2014 (\$ 90,000), from the Swedish multinational Getinge, a company operating in the field of medical techniques. The present competition with the use of ethylene oxide (still accepted despite all its carcinogenic, greenhouse and even toxic (lethal) disadvantages for humans) makes our system, for the moment, economically unprofitable.

Patents

The fact that 35 patents (many of Air Liquide applications constituting a *family* possibly counting up to 50 countries) were filed was recognized by the 2017 Innovation Award granted by the European Physical Society. Noteworthy patents: surfatron and surfaguide (e.g. US 4 049 940 (1977)). These are EM field applicators serving to generate microwave sustained gas discharges, mostly in the form of surface-wave (SW) plasma columns. Worldwide usage: 1/3 of surfaguide and almost ½ of surfatron mentions in papers no longer refer to the inventors: it has become a lab tool. In passing, the surfatron was part, at one point, of an ion-plasma source launched at Baikounour as part of a French-USSR joint experiment (1989) for surveying Phobos surface (Mars satellite): a Kr ion-plasma source (DION) designed for SIMS measurements equipped with a surfatron chosen because of its light weight and perfect reliability of operation under pre-launching stress tests.

A series of patents (own by Air Liquide), in particular for the Universal Plasma Abatement System (UPAS), for eliminating greenhouse gases in microelectronics fabs (e.g. SF₆, CF₄) and, more important for the company, for purifying krypton and xenon gases obtained from cryogenic distillation of air, Xe being used, for example, as ion-thruster "fuel" to reposition daily communication satellites (very high purity Xe required for an envisaged 25 year life-time of the satellite). Both techniques are fully *green* (Air Liquide is actually controlling the xenon world market with this low-cost, ecological and high-level purification technique). Details on Patents on pages 38-50.

Research financing

Besides industrial contracts (e.g., 3.47 M\$ from Air Liquide plus government contributions), an absolutely continuous sponsoring by NSERC (Canada federal research council) with my (possibly) last individual (*discovery*) grant coming to an end on March 31 2022.

Scientific achievements

1) Generation, experimental data gathering and modeling of surface-wave (SW) sustained plasma column.

The perfectly reproducible properties of SW plasmas obtained with surfatron and surfaguide devices as EM field applicators (wave launchers: Moisan and Zakrzewski, J. Phys. D: Appl Phys. 1991) paved the way to the generation, observation and modeling of RF and microwave surface-wave sustained discharges (SWDs). Research interest on this topic showed up in most European countries including Russia besides Middle-East (in particular Iran), China and Japan. The surprising features of SWDs, particularly the fact that the plasma column can extend far away from the field-applicator (up to 4.5 m demonstrated) attracted and puzzled many scientists. Also noteworthy is that SWDs provide the broadest operating range of all plasma sources: from reduced gas pressure (mTorr, through ECR conditions) up to at least 10 times atmospheric pressure, field frequency ranging from \approx 10 MHz up to 40 GHz, discharge tube diameter from 1 mm to at least 300 mm, features that generated extended modeling and specific applications such as *greenhouse* gas remediation, rapidly reconfigurable (warfare) antennas, to mention only a few. The TIAGO plasma torch (patented too), which also provides a SWD, is a highly efficient plasma source for generating all kinds of materials (e.g., abundant graphene "powder").

Noteworthy of mentioning besides SWDs is the original plasma system where the applied EM *E*-field is confined within a volume smaller than that of the plasma generated determined by antenna aperture. It allowed a unique demonstration of periodic (ion plasma oscillations) parametric instabilities that were predicted to occur in an extremely high intensity *E*-field. By the same token, it showed how to raise the intensity of EM fields to achieve higher excitation, ionisation and molecular dissociation rates, a clear way of attaining higher process efficiencies (Moisan and Nowakowska, PSST (Topical review) 2018).

2) Sterilization using SWD plasmas.

A thorough investigation of the “good and bad properties” of using SWDs to perform sterilization of bacterial spores (the toughest to inactivate micro-organisms) and to eliminate pathogenic prion proteins (Creutzfeld Jakob disease) has been conducted and reported in the European physical journal of applied physics, as an invited paper. A specific method for sterilizing medical devices (MDs) was elaborated that called on the late flowing-afterglow (absence of charged particles) of a N₂-O₂ discharge, which creates enough (and therefore irreversible) lesions to the micro-organisms DNA through UV irradiation. The UV photons are provided by NO molecules resulting from the combination of N and O atoms obtained from the dissociation of the N₂ and O₂ molecules in a SWD, providing a broad UV (180-350 nm) spectrum. The N and O atoms can infiltrate in-between stacks of spores before turning into NO molecules, ensuring better spore inactivation than direct UV irradiation from excited/metastable state atom/molecule (not to mention UV light) (Moisan et al., *Europ. Phys. J. Appl. Phys.* 2014). Nonetheless, possibly the most important result from our work, applicable to all plasma sterilization methods, is the fact that bacterial spores get charged up with electrons in a discharge, and then these microorganisms are released (most of them having not been inactivated yet) at the very initial stage of the sterilization process by electrostatic force: this point had escaped researchers and is still not recognize as it “impairs the real potential and validity of all sterilization methods taking place in discharges” (Moisan et al. *J. Phys. D: Appl. Phys.*, 2014). Our late flowing-afterglow system received industrial approval (Getinge Healthcare UK), but it implied a higher operating cost as compared to Ethylene oxide (EtO), of worldwide use, although toxic (at the ppm level) and on the long run, at lower levels, cancerogenous, additionally a *greenhouse* gas and a potentially explosive gas;

3) concerning the most recent advances:

- a) the documented disclosure of the antenna-like region (space-wave radiation) that precedes SWD generation (Moisan et al., AMPERE Newsletter 2019). Our experimental study and analysis of this region throw some specific light on this region, which was ignored although SWDs had become the subject of many publications. It shows, in the end, that the EM radiation coming out from SWD (and spreading into the ambient) is not related to the EM radiation from the SW plasma column, but to this antenna-like far-field radiation region, which can be eliminated by surrounding the SWD with a Faraday cage at (circular waveguide) wave cut-off. Since it reduces radiative power loss, it increases the plasma column length (larger total number of electrons in the SWD) (AMPERE Journal attached);
- b) the SW propagates along the dielectric discharge tube without being influenced by the properties of the plasma column: a change in paradigm. I have demonstrated from available experimental results that the plasma column properties do not affect the SW features. Theorists had all assumed that the SW properties depended on the plasma column, which leads to results in contradiction with experiments at the plasma column end, as elaborated in a manuscript to be submitted shortly.

c) I have developed and significantly expanded the power per electron concept (manuscript ready for submission). This approach, initially limited to microwave discharges (such that only electrons gain energy from the EM field) provides additional light not only on microwave discharge operation and mechanisms but, qualitatively, to all kinds of discharge. In particular, it shows that confining the EM field sustaining the discharge to a volume smaller than that of the plasma volume leads to increasing the intensity of the (maintenance) EM electric field component, allowing higher efficiency processes such as molecular dissociation. Using earlier the power per electron procedure, it had been shown (2018 PSST paper) that the *E*-field intensity is an internally-set quantity, not directly related to the power or voltage applied by the operator. A further issue of our model concerns pulsed-operated discharges. It shows that pulse time duration and repetition rate can be adjusted to reach the highest possible *E*-field intensity, a valuable feature when, for example, looking for the most efficient discharge for splitting CO₂ molecules.

In conclusion, my work started with the invention of surfatron and surfaguide *E*-field applicators generating surface-wave plasma columns of the utmost (and puzzling) interest for lab work, discharge modeling and industrial/lab related original inventions: I not only participated in all these aspects, but often I was the initiator of a topic that developed afterwards. A sideline of my work, but closely related to the availability with SWDs of a N₂-O₂ late afterglow (no ions present), led to propose achieving *green* and efficient sterilization of dielectric made MDs. Although I am basically an experimentalist, almost all my publications comprised some degree of explanations of the physical phenomena involved, often accompanied by original modeling concepts.

Publication metrics (May 2023):

Approximately 150 peer-reviewed articles, with an average paper length over last 10 years of 18 pages. 21 papers are cited at least 100 times and a H index of 44 according to Web of Science (Clarivate) while Google Scholar yields an H index of 54 with 13094 total number of citations.

Complementary material

Congratulation e-mail about 2017 Innovation Award from the President of the Russian Academy of Sciences

De : Глуховцева О.Э. [mailto:oeglukhovtseva@presidium.ras.ru]

Envoyé : 16 mars 2017 08:11

À : michel.moisan@UMontreal.CA

Objet : Congratulations

Dear Professor Moisan,

Please find attached a letter from the President of the Russian Academy of Sciences Academician V.E. Fortov.
Yours sincerely,

Olga Glukhovtseva

Head
Foreign Relations Department
Russian Academy of Sciences

Prof. Michel Moisan,
Université de Montréal
Québec, Canada

Dear Professor Moisan,

On behalf of the Organizing Committee of the International Conference “Physics of Low Temperature Plasma” (PLTP-2017, Russia, Kazan, 5-9 June, 2017) and from myself personally allow me to congratulate you on being awarded the Prize of the Plasma Physics Division of the European Physical Society “The 2017 Innovation Award” for “pioneering contributions to the development and understanding of microwave plasma sources and their applications for materials processing, healthcare and environmental testing”.

Your outstanding contribution to the physics of low-temperature plasma and gas discharges cannot be overemphasized. It is a great honour for us that you are the member of the Organizing Committee of the PLTP-2017.

We wish you continued success in your work.

Sincerely,

Professor
Vladimir Fortov

President of the Russian Academy of Sciences,
Chairman of the Organizing Committee of PLTP-2017

Position offered to put up a plasma physics department at the Epidemiology and Microbiology Magalaya Institute (Moscow), Academy of Medecine

In March 2016, members of this Institute (where the Sputnik V vaccine was conceived) proposed to hire me in the frame of their program « collaboration projects with prominent foreign researchers » to establish and run a plasma lab destined to medical studies. I had to refuse because I had to go through an immunotherapy treatment for leukemia (from January to July 2017).

Scientific collaboration with companies

Québec companies

Métal 7, Sept-Îles

Company using very high power plasma torches.

Peintures Prolux (Paints), Montréal

We have conceived a (microwave) plasma afterglow technique to increase paint adhesion on recycled polymers (of various origin). Prolux found a less costly plasma system than ours, but they use it with « our recipe ».

Fordia, Montréal

Company own description: « Global solutions for drilling providing a large range of diamond coated tools for mine and geotechnic surveys... ». At that time, I had a team of 3 researchers working on obtaining high quality polycrystalline diamond deposits, which led us to file a patent which shows how to obtain a greater adhesion on ferrous surfaces. US [5,759,623](#)

Outils Gladu, Marieville

Manufacturer of diamond (and diamond-like) coated tools. Same topics and objectives as for Fordia above..

MPB Technologies (space and photonic division), Pointe-Claire

We participated with MPB in the Federal program called Stear VI aiming at ensuring that the materials covering the space shuttle and other satellite surfaces can resist to oxygen collisions (interaction) in the upper atmosphere.

BOMEM, Québec

Design and realization of a microwave sustained plasma adapted to the detection of analytical signals from gaseous chromatography systems using the Ro-Box field applicator (operating frequencies as low as 27 MHz.). US [4,810,933](#). Actually, we assembled a 40 MHz transistored (300 W) power supply to go along with the plasma source. The company manufactured top Fourier-transform spectrometer. Québec FCAR financing program sponsoring this collaborative work.

CELL FOODS, Pointe-Claire

A company selling spices (e.g., coriandre, paprika) after using ethylene oxide to make sure that their product is free from micro-organisms. Such a decontamination method (potentially toxic for employees and cancerogenous for consumers) is not accepted by EC.regulations. Our N₂-O₂ flowing afterglow was shown, in contrast, to be totally safe and *green*. However, the handling of powder would have required a specific engineering technique to ensure that all the spice-powder grains, in their entirety, would be exposed to the late flowing-afterglow of the N₂-O₂ discharge during the process.

American companies

XEROX, Webster, N.Y.

Potential and limitations of microwave deposition technologies for Xerox's critical materials need. In January 1998, we delivered to Xerox a surfaguide (SW) plasma source and then participated in the training of their personnel on microwave sustained discharges. We provided the required modifications to improve and optimize their plasma reactor. Non-disclosure agreement (NDA) signed.

IBM, Yorktown Heights and Essex Junction, N.Y.

Microwave-plasma etching of polyimide (part of the process of chip manufacturing).

The Company wanted my group to check polyimide etching with a 2450 MHz sustained discharge. A plasma reactor of our own was designed and put up that could operate from 13.56 MHz to 2450 MHz, allowing looking for the EM field frequency that would provide the fastest etching and be the less damage to polyimide samples. Such a possibility of using the same plasma configuration throughout such frequency span ensured determining the sole influence of the field frequency on etching rate, if any, and on substrate heating. Contrary to the initial solution promoted by IBM engineers, we showed that such etching must not be performed at 2450 MHz (not only etch rate was very low but there was overheating leading to destruction of the polyimide substrate), but rather at 27 MHz. According to "my" manager at Yorktown Heights, avoiding a 2450 MHz etching process of polyimide on production line saved millions of dollars to the Company.

SINGER (gyrolaser guidance and navigation Kearfott division), Little Falls, N.J.

NDA signed to examine the substitution of DC discharges by a high frequency (HF) discharge for gyrolaser (ring lasers configuration) systems operation for increased reliability in trajectory guidance.

Fusion system, Rockville, MD

NDA on high power UV lamps using microwave sustained plasma technology.

SOHIO (Standard oil of Ohio) (1982-1984)

Frequency dependence of the deposition rate of amorphous Si:H produced by a surface wave (surfatron) generated plasma.

WESTINGHOUSE (lighting division) (1980-1981) at Pittsburgh

NDA on various aspects and possibilities of using SWDs for lighting purposes.

Elsewhere in the world

ICI (Imperial Chemical Industries), Manchester, EnglandAngleterre

Novel microwave plasma techniques and treatments (material eposition).

NDA, meeting in Manchester (December 1985) leading to a significant research contract. With Professor Zakrzewski (invited professor) a microwave-field applicator was designed (the main point for ICI was coming up with a system not already covered by a competitor patent). Two different, efficient, leaky-wave-antenna system were designed, additionally paying attention. Moreover, numerically solved plasma and Maxwell equations were numerically solved to yield the radiated EM field.

SNLS, St-Romans, France

The multipolar magnetically confined plasma-reactor, designed at the Centre National d'Études des Télécommunications (CNET) of Grenoble, was equipped with a waveguide-surfatron.

SAIREM, Neyron, France

Designer and manufacturer of radio-frequency and microwave generators and of EM field applicators to go along with these generators as well as for corresponding industrial applications. I have been acting as consultant for this company since 1994 and their first sales of surfatrons started in 1998 (more than 100 sold). The surfaguide is now marketed by SAIREM (see their site).

GETINGE HEALTHCARE, Getinge, Sweden

This company defines itself as the leader in infection control solutions in healthcare centers, public or private. The Getinge Infection Control entity, according to its own advertisement, promotes innovation and technological progress in the fields of disinfection and sterilization, having a global presence with 31 subsidiaries spread over five continents. This company secured for the year 2013-2014 a license for our patents in sterilization / disinfection for evaluation. Our R&D work in this area received a positive review from Getinge Infection Control (UK) and its subsidiary La Calhène (Vendôme, France). However, the cost of implementing and operating our device is not competitive with the ethylene oxide sterilization process currently used by Getinge.

Edition of books and text-books

As publisher (implementation of a collective work):

With Jacques Pelletier (Grenoble): Microwave excited discharges (Elsevier, 1992; reprinted in 2005).

With C.M. Ferreira : Microwave discharges : fundamentals and applications (NATO ASI Series, 1992).

Publication of a manual on plasma physics and a manual on atomic physics and optical spectroscopy (in French).

Physique des plasmas collisionnels (2006), by M. Moisan and J. Pelletier, published by editions EDP (France). A second edition, revised and enlarged (80 additional pages for a total of 504 pages), entitled (english translation) Collisional Plasma. Physics of RF and Microwave Discharges has been available since 2014. The publication of this manual in English (2012) by Springer Verlag seems to be well appreciated, more than 1000 downloads (between July 2013 and the end of December 2014). The impact of scientific

books is now measured not only by the number of copies sold, but also by the number of downloads (those controlled by the Publisher!).

Physique atomique et spectroscopie optique, by M. Moisan, D. Kéroack and L. Stafford (455 pages including 46 problems with complete solution), appeared in July 2016 under EDP editions (Grenoble-sciences collection) (France).

Chapters in books

1. Zakrzewski Z., Stanco J., Moisan M., *Modeling of atmospheric pressure microwave sustained discharges*, in *Advanced technologies based on wave and beam generated plasmas*, A. Shivarova, Editor. 1999, Kluwer Academic Publishers NATO Science Series, High Technology. p. 343-352.
2. Zakrzewski Z., Moisan M., *Long microwave discharges*, in *Advanced technologies based on wave and beam generated plasmas*, A. Shivarova, Editor. 1999, Kluwer Academic Publishers NATO Science Series, High Technology. p. 353-365.
3. Zakrzewski Z., Moisan M., *Atmospheric pressure discharges: traveling wave plasma sources*, in *Advanced technologies based on wave and beam generated plasmas*, A. Shivarova, Editor. 1999, Kluwer Academic Publishers NATO Science Series, High Technology. p. 335-342.
4. Moisan M., Hubert J., Margot J., Zakrzewski Z., *The development and use of surface-wave discharges for applications*, in *Advanced technologies based on wave and beam generated plasmas*, A. Shivarova, Editor. 1999, Kluwer Academic Publishers NATO Science Series, High Technology. p. 23-64.
5. Wertheimer M.R., Martinu L., Moisan M., *Microwave and dual-frequency plasma processing*, in *Plasma processing of semiconductors*. 1997, NATO ASI Series. p. 101-127.
6. Margot J., Moisan M., *Physics of surface-wave discharges*, in *Plasma processing of semiconductors*. 1997, NATO ASI Series. p. 187-210.
7. Margot J., Chaker M., Moisan M., St-Onge L., Bounasri F., Dallaire A., Gat E., *Magnetized surface-wave discharges for submicrometer pattern transfer*, in *Plasma processing of semiconductors*. 1997, NATO ASI Series. p. 491-513.
8. Moisan M., Margot J., Zakrzewski Z., *Surface Wave Plasma Sources*, in *High density plasma sources*, O. Popov, Editor. 1995, Noyes Publications. p. 191-250 (chap. 195).
9. Zakrzewski Z., Moisan M., Sauvé G., *Surface-wave plasma sources*, in *Microwave discharges: fundamentals and applications*, C.M. Ferreira and M. Moisan, Editors. 1993, Plenum Publishing. p. 117-140.
10. Moisan M., Hubert J., Margot J., Sauvé G., Zakrzewski Z., *The contribution of surface-wave-sustained plasmas to HF plasma generation, modeling and applications: status and perspectives*, in *Microwave discharges: fundamentals and applications*, C.M. Ferreira and M. Moisan, Editors. 1993, Plenum Publishing. p. 1-24.

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NB: My latest manuscript, still in progress, available in arXiv as paper 2106.11404 Plasma columns generated by the propagation of an electromagnetic surface wave have no effect on the properties of the wave, contrary to what is generally advocated. They in fact depend only on the discharge operating conditions, specifically wave frequency, tube radius, gas nature and density*

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Popularization article published in the British magazine *Scientia*

Moisan M. (2023) Providing stable and power-efficient plasma using microwaves. To appear in the *Scientia* issue of July 2023. 5 pages.

Invited conferences²

1. Moisan M., Nowakowska H. (2019) Generation and modeling of gaseous plasmas using microwave power. *17th International Conference on Microwave and High Frequency Heating (AMPERE 2019)*. Proceedings pages 27-34. ISBN: 978-84-9048-719-8. DOI: <http://dx.doi.org/10.4995/Ampere2019.2019.9989>. (**Spain**). Note: Key-Note Speaker.
2. Moisan M., Levif P., Nowakowska H. (2018) Unrevealed feature of surface-wave sustained tubular discharges (SWDs): space-wave radiation region in the immediate vicinity of the wave launching interstice before the SWD develops. *10th workshop on microwave discharges (MD-10)*, Zvenigorod (Moscow oblast). Proceedings pages 97-110. (**Russia**).
3. Moisan M., Nowakowska H. (2017) The remarkable contribution of surface-wave sustained plasma columns to the modelling of RF and microwave discharges. In this plenary session, the 2017 Innovation Prize of the European Physical Society (Plasma physics division) was awarded to M. Moisan at its 44th Annual meeting in Belfast (**UK**).
4. Moisan M. (2015) The power θ_a absorbed per electron from the E-field and the power θ_l lost per electron under various processes as meaningful physical parameters allowing characterizing and modeling DC, RF and microwave discharges as functions of operating

² Many-in-person conferences that I intended to attend in 2020-2021 were cancelled: I particularly regret the (invited) conference (Workshop on microwave discharges) that was planned to take place in Kazan, Tatarstan (Russian Federation). On the other hand, I did not feel at ease with providing *zoom* (or other similar means) conferences.

- conditions. IX International workshop on microwave discharges: fundamentals and applications, Cordoba (**Spain**). Note: inaugural presentation.
5. Moisan M., Levif P., Séguin J., Barbeau J. (2013) Sterilization/disinfection using reduced-pressure plasmas : comparison between direct exposure to a discharge and to a flowing afterglow *Central European Symposium on Plasma Chemistry (CESPC-5)*, Balatonalmadi (**Hungary**). Note : inaugural presentation.
 6. Kilicaslan A., Roy-Garofano V., Levasseur O., Stafford L., Moisan M., Côté C., Sarkissian A. (2013) Formation dynamics of organosilicon and organotitanium nanopowders in microwave-sustained plasmas at atmospheric pressure. *Congrès de l'ACP Montréal (Québec)*.
 7. Stafford L., Boucher A., Iarotsky L., Hamady M., Moisan M. Development and characterization of a new microwave plasma source in contact with liquids. (2013). *Congrès de l'ACP Montréal (Québec)*.
 8. Moisan M., Levif P., Séguin J., Barbeau J. (2013) Stérilisation de dispositifs médicaux par plasma à pression réduite : comparaison des avantages et inconvénients d'une exposition directe à la décharge relativement à une post-décharge (2013). Congrès de l'Association Canadienne des Physiciens (ACP), Montréal (**Québec**).
 9. Moisan M., Levif P., Séguin J., Carignan D., Kéroack D., Barbeau J., Leduc A., Elmoualij B., Gofflot S., Heinen E., Thellin O., Zorzi W., Kutasi K. (2012) The flowing afterglow of the N₂-O₂ discharge as a means of decontaminating/sterilising through UV radiation: summary of the results achieved and recent results. *The 39th IEEE International conference on plasma science (ICOPS2012)* Édimbourg (**UK**).
 10. Moisan, M., Using gaseous plasmas to inactivate microorganisms: a possible alternative to conventional sterilization techniques (2011) Institut d'immunologie Cantacusino, Bucarest (**Romania**).
 11. Moisan M., Barbeau J., Boudam M.K., Carignan D., Levif P., Séguin J., Soum-Glaude A. (2010) Sterilization of medical devices using plasma: advantages and limitations. The reduced-pressure flowing-afterglow of the N₂-O₂ discharge as the biocidal medium. *11 th High-Tech Plasma Conference (HTPP-11)*, Bruxelles (**Belgium**).
 12. Moisan M., Pelletier J. (2009) Advances and drawbacks of microwave plasmas. *7th workshop on microwave discharges (MD-7)* Hamamatsu (**Japan**).
 13. Castaños-Martínez E., Moisan M. (2009) Expansion and homogenization of rare-gas tubular discharges at pressure higher than 1kPa. *7th workshop on microwave discharges (MD-7)* Hamamatsu (**Japan**).
 14. Castaños-Martínez E., Moisan M. (2009) Determination of metastable and resonant atom densities through spectral-lamp absorption spectroscopy at atmospheric pressure. *7th workshop on microwave discharges (MD-7)* Hamamatsu (**Japan**).
 15. Castaños-Martínez E., Moisan M. (2009) Expansion of contracted single rare-gas tubular discharges at atmospheric pressure. *52nd SVC (Society of Vacuum Coaters) Annual Technical Conference* Santa Clara, Californie (**USA**). Proceedings available through SVC Library (ISSN 0737-5921), pp 333-338 (2009).

16. Moisan M., Boudam M.K., Kéroack D., Pollak J., Saoudi B. (2008) Caractérisation de l'inactivation de micro-organismes par les photons UV/UVV émis par une décharge d'argon ou dans une post-décharge de N₂-O₂: fluence (dose), longueur d'onde des photons, dommage aux matériaux. *colloque Plasma-Québec* Montréal (**Québec**).
17. Moisan M., Boudam M.K., Pollak J., Saoudi B. (2007) UV based plasma sterilization in an argon discharge and in an N₂-O₂ flowing afterglow: development of 3 different plasma sterilizers. *International Conference on Plasma Medicine (ICPM)-I* Corpus Christi, Texas (USA).
18. Kabouzi Y., Nantel-Valiquette M., Makasheva K., Castaños-Martinez E., Moisan M., Rostaing J.-C. (2006) Reduction of PFC emissions using atmospheric-pressure microwave plasmas: mechanisms and energy efficiency. *6th International workshop on microwave discharges* Zvenigorod (**Russia**).
19. Benhacene Boudam K.M., Popovici C., Moisan M., Saoudi B., Gherardi N., Massines F. (2006) Bacterial spore inactivation by UV photons in atmospheric pressure discharges. *18th ESCAMPIG* Lecce (**Italy**).
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21. Moisan M., Barbeau J., Benhacene Boudam K.M., Crevier M.C., Pelletier J., Philip N., Saoudi B. (2003) La stérilisation d'objets médicaux au moyen d'un plasma (gaz ionisé) : une alternative aux méthodes actuelles de stérilisation. *71^e Congrès de l'ACFAS* Université du Québec à Rimouski (**Québec**)
22. Moisan M. (2003) Recent development in the application of microwave discharges to the sterilization of medical devices. *5th International workshop on microwave discharges* Zinnowitz, Greifswald (**Germany**). Abstracts and program.
23. Moisan M., Kabouzi Y., Kéroack D., Rostaing J.C., Guérin D., Larquet C., El-Krid A. (2002) Abatement of greenhouse perfluorinated gases in atmospheric-pressure surface-wave microwave plasmas. *4th Int. workshop on fluorocarbon plasmas* Col de Porte, Grenoble (**France**).
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31. Moisan M. (1998) Characteristics of surface-wave excited plasmas. *The 15th symposium on plasma processing* Hamamatsu (**Japan**) Procedings from the symposium, 160-165.
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Other conferences not reported (265 participations in Conferences in numerous countries)

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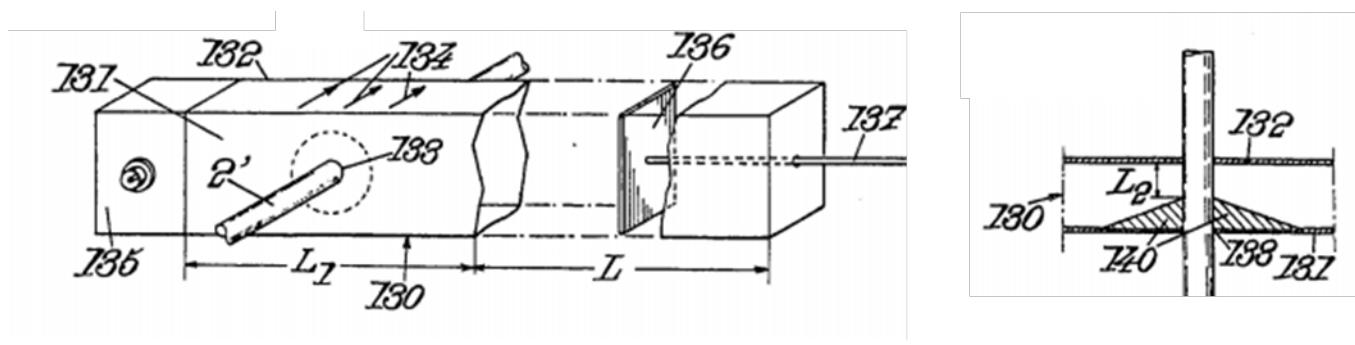
Photo and schematic descriptions of some of the devices and systems patented by Moisan (with comments)

1- EM field applicators for sustaining gaseous discharges

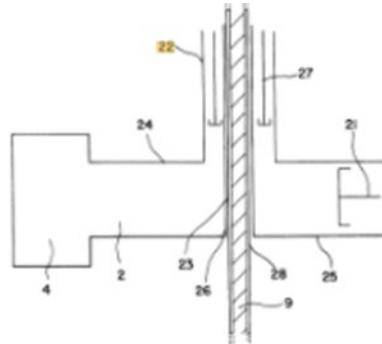
Surfatron



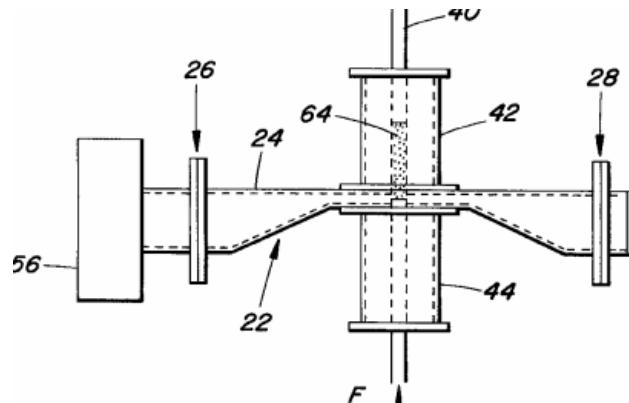
Surfaguide (first design). (left) Microwave power supplied directly to the waveguide through a coaxial cable (entry 135). (right) Internal impedance transformer at the interstice location



Surfatron-guide (waveguide-surfatron) (two impedance tuning means, 21 and 27. No tapering down of the waveguide at the *launching* interstice, but direct waveguide power feeding (higher power level operation).



Surfaguide (commonly adopted design) Tapering down of the waveguide narrow wall at the interstice.

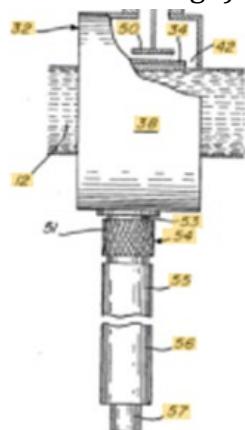


Only one impedance tuning means (56). MW waveguide power input (before 28).

The tapering of the waveguide narrow wall with its gradual transitions plays the role of impedance transformers. When the height of the narrow wall section is appropriately chosen, the surfaguide characteristic impedance at the interstice aperture is (approximately) made equal to that of the characteristic impedance of the surface-wave plasma column (considered as a transmission line). The reflecting plane (short-circuiting plane of the wave) axial position in the waveguide then no longer needs to be adjusted as operating conditions are varied in contrast to previous surfaguides and waveguide-surfatrons designs., a precious industrial operating feature.

NB: Many researchers believe that the narrower the surfaguide diminished wall height, the more intense is the *E*-field of the wave on the discharge tube. Experiments show that shortening too much the narrow wall height affects negatively the impedance matching, which not only becomes bad, but varies with operating conditions.

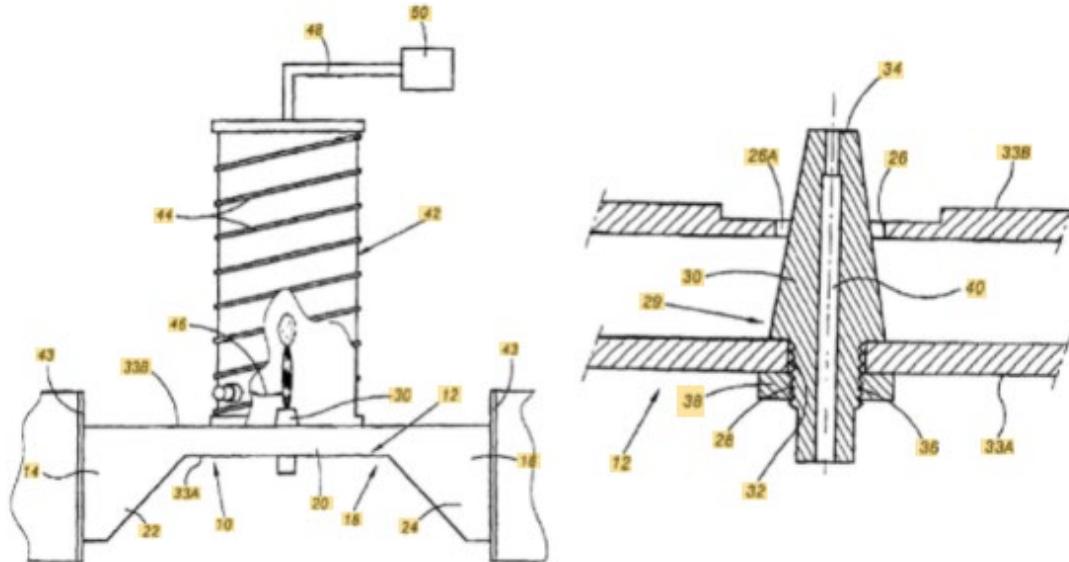
Ro-Box (stub Ro-Box design)



Stub: a conducting cylinder (55-56) in which an internal piston 57, ending with a short-circuiting conducting plane, allows sliding it for impedance matching.

TIAGO

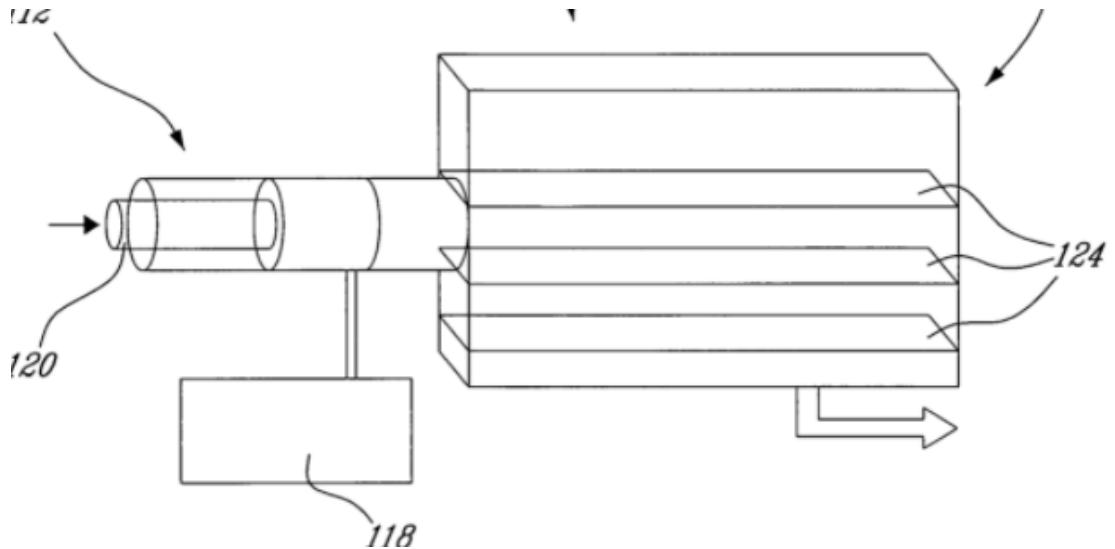
A plasma torch system where a gas flow (e.g. argon) exits at a (conducting) nozzle past which a surface-wave (SW) discharge is sustained at atmospheric pressure, either in the ambient or within a confining vessel. Microwave power is transferred to the nozzle either from a surfaguide field-applicator or directly along a nozzle (30) partly inserted in a waveguide, perpendicularly to its axis. The broad wall material is thinned (26) around the conical nozzle, which is separated from the wall by an air space 25A.



(left) TIAGO system within a sealed (and water cooled) vessel (many kW device) or (right) exiting in the ambient (low power system, with possibly many of them distributed along the waveguide).

N₂-O₂ SW flowing afterglow design of a sterilization chamber.

Inside the chamber there are, e.g., supporting plates for the medical devices (MDs) to be sterilized. Inactivation takes place due to UV (180-350 nm) irradiation by the NO molecules formed by combination of N and O atoms. These are provided by a surfatron discharge that dissociates the N₂-O₂ gas mixture into N and O atoms. At a short enough distance from the chamber, the plasma source provides into the chamber an early flowing afterglow (ions are present) whereas at a far enough distance (>820 mm), the late afterglow entering the chamber is free from electrons and ions (preventing microorganisms from being released (due to electrostatic charging by electrons) from their substrate before being inactivated).



List of patents (applied for/granted). A given patent application can be filed in many countries, resulting in a *family* of patents

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3. M. Moisan, Z. Zakrzewski, "New surface wave launchers to produce plasma columns and means for producing plasmas of different shapes", Canadian patent 1,246,762 (Dec. 1988), US patent 4,810,933 (March 1989). Assignee: Université de Montréal, patemt acquired later on by Air Liquide *Ro-Box (EM field applicator operating below 100 MHz) for sustaining surface-wave plasma columns..*
4. M. Moisan, Z. Zakrzewski, "New surface wave launchers to produce plasma columns and means for producing plasmas of different shapes", Canadian patent 1 273 440 (a division of the Canadian parent patent. 1,246,762) (August 1990), US patent 4 906 898 (March 1990) (a division of US parent patent 4,810,933). Assignee: Université de Montréal, patemt acquired later on by Air Liquide. *Surface-wave plasmas allows achieving various shapes of discharge vessel (lighting lamp shapes)..*
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8. Same authors as above in 7: US 6 290 918, a division of the US parent patent 5,965,786. *Process as described above, indicating that the plasma is obtained by the propagation of a surface wave (achieved with a waveguide-surfatron).*
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11. M. Moisan, R. Etemadi, J. C. Rostaing, "Dispositif d'excitation d'un gaz par plasma d'onde de surface et installation de traitement de gaz incorporant un tel dispositif", french patent 2 762 748 (filed : 25 April 1997 ; publication: 31 October 1998), European patent application, EP 0874537 A1 (21 April 1998). Designated countries: AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE, « Extended » countries designated : AL LT LV MK RO SI. "Device for exciting a gas by a surface wave plasma and gas treatment apparatus incorporating such a device", US 6,224,836 (01/05/2001), Canadian 2,235,648 (25/10/1998). Assignee: Air Liquide. *A device for exciting a gas (describing the surfaguide EM field applicator) through which (perpendicularly) passes the discharge tube for the purpose of producing a surface-wave plasma, the discharge tube being surrounded by a conducting (Faraday) cage "to concentrate microwave radiation".*
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2 787 677 (filed 22/12/1998), European EP 1014761 (filed 03/12/1999), US 6 541 917 (01/04/2003). Designated countries : AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE. Assignee: Air Liquide. *Surfaguide EM field applicator for treating a gas by achieving a surface-wave plasma in a tube that "comprises, over at least part of its length, a double wall".*

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15. J.C. Rostaing, D. Guérin, C. Larquet, C. H. Ly, M. Moisan, H. Dulphy, "Application des plasmas denses créés à pression atmosphérique au traitement d'effluents gazeux", French patent application number 0107150 (31/05/2001). PCT application (21/05/2002) published (05/12/2002) under number WO02097158. French patent : FR 2 825 295 (06/12/2002), EP1397529 (2004-03-17), US patent application 2004/0195088, CN1543515 (2004-11-03), DE60218305T (2007-11-15). Assignee: Air Liquide. *System for treating gases such as pfc or hfc with plasma, diluted into N₂, comprising pumping means such that the outlet is at a pressure substantially equal to atmospheric pressure such as to produce a plasma (waveguide-surfatron) at atmospheric pressure.*
16. • J.C. Rostaing, D. Guérin, C. Larquet, C. H. Ly, M. Moisan, H. Dulphy, Referring to entry 15, the present US patent application 2010/0155222 is a division of US parent patent application 2004/0195088 . Assignee: Air Liquide. *The system ensuring the process is descred. For safety reasons, the gaseous effluents coming from the reactor or from the production chamber are, downstream or in the exhaust of the roughing pump or the rough-vacuum pumping, set highly diluted in nitrogen (with an additive gas, namely oxygen) or air at substantially atmospheric pressure.*
17. M. Moisan, J. C. Rostaing, M. Carré, K. C. Tran, "Procédé de traitement des gaz par des décharges hautes fréquences", French patent FR 2 864 795 PCT application published on 18 August 2005 under number WO2005075058, KR20060128905 (2006-12-14), EP1703961 (2006-09-27), US patent application 2007/0284242 (2007-12-13). Assignee: Air Liquide. *RF (ICP) inductive discharge for purifying gases containing impurities.*
18. Y. Kabouzi, M. Moisan, J. C. Rostaing, D. Guérin, H. Dulphy, P. Moine, V. Laurent, B. Depert "Traitement d'effluents gazeux par plasma à pression atmosphérique", French patent FR 2 873 045 (filed as FR0451527 on 13/07/04), PCT application WO2006008421 published on 26/01/2006), CN101065182 (31 October 2007). Assignee: Air Liquide. *Swirling flow (vortex) gas input at atmospheric pressure increases plasma destruction efficiency of fluorinated effluents (in fact by 15%).*
19. Z. Zakrzewski, D. Czyskowski, M. Jasinski, M. Moisan, D Guérin, C. Larquet, J. C. Rostaing, "Excitateurs de plasma micro-ondes", French patent FR 2 880 236, PCT application as WO 2006090037 (published on 31/08/2006), US 7 799 119. Assignee: Air Liquide. *A variant of the surfaguide field applicator where the narrowing of the wall (to ensure adequate impedance matching, at the launching interstice, with the surface-wave plasma column "seen as a transmission line" of given characteristic impedance) is arranged within a standard*

section of the waveguide, reproducing inside the waveguide similar step-transitions as achieved with the tapering down of the genuine surfaguide.

20. D. Guérin, C. Larquet, A. El-Krid, J.-C. Rostaing, M. Moisan, P. Moine, H. Dulphy, A.L. Lesort, E. Sandre, "Procédé de traitement, par plasma, d'effluents gazeux", French patent FR 2 888 519 (filed FR0552149 on 12 July 2005), EP1904664 (2 April 2008), Korea KR20080032089 (14 April 2008). PCT application as WO2007007003 (published on 18/01/2007). Assignee: Air Liquide. *Plasma torch system for treating gaseous effluents substantially at atmospheric pressure with water vapour injection, up and downstream the generated plasma.*
21. Y. Kabouzi, M. Moisan, J-C Rostaing, D. Guérin, "Traitement d'effluents gazeux par plasma à pression atmosphérique", French patent application FR04515227 on 13 July 2004. French patent FR 2 873 045. Assignee: Air Liquide. *Swirling gas flow injection (first design).*
22. H. Dulphy, P. Moine, V. Laurent, B. Depert, Y. Kabouzi, M. Moisan, J. C. Rostaing, D. Guérin, "Traitement d'effluents gazeux par plasma à pression atmosphérique", French patent FR 2 888 130 (2007-01-12), PCT WO2006008421 (2006-01-26), EP1768776 (2007-04-04), US application 2008 0234530 "Gas conversion by chemical bond cleavage in an electric and-or magnetic field, e.g. for treatment of fluorinated effluents from semiconductor production, involves injecting gas into the field in a non-rectilinear manner". Assignee: Air Liquide. *A device providing a swirling flow for the treatment of fluorinated effluents by surface-wave plasmas (electric field) to increase the effectiveness of the conversion of the gas or gas mixture molecules.*
23. C. Larquet, D. Guérin, J-C Rostaing, H. Dulphy, M. Moisan, "Procédé et dispositif de traitement d'effluents gazeux de procédés industriels", French patent FR 2 886 866 (2006-12-15) (Filed 9 June 2005). Assignee: Air Liquide. *TIAGO plasma torch system within a sealed vessel comprising cooling means (intended for TIAGO industrial gas remediation unit operating at 10s of kW).*
24. •M. Moisan, D. Guérin, C. Larquet, J.-C. Rostaing, A.L. Lesort, A. El-Krid, H. Dulphy, P. Moine, B. Depert, V. Laurent, E. Sandre, "System for the destruction of PFC molecules using an aluminum nitride comprising dielectric tube". European application as EP 08305205.0 filed on 28 May 2008. Assignee: Air Liquide. *System for the destruction of PFC molecules using an aluminum nitride comprising dielectric tube.*
25. •J.-C. Rostaing, D. Guérin, C. Larquet, P. Moine, B. Depert, V. Laurent, M. Moisan." Procédé de refroidissement d'un plasma micro-onde et système de destruction sélective de molécules chimiques utilisant ce procédé". Patent applications European EP2131633 (2009-12-09), US 2011073282, TW200352568, KR201100121816, JP2011522691, WO2009144110. Methods for cooling the discharge tube in microwave abatement system. Assignee: Air Liquide. *A process for selective destruction of chemical molecules where the coolant flow is in thermal contact with the outer wall of the tube to be cooled, the coolant is a linear alpha-polyolefin oil having a carbonated chain of at least ten carbon atoms and/or perfluorocarbonated liquids having a dielectric permittivity lower than 2.5, a microwave loss tangent tan δ between 10⁻² and 10⁻⁴, and a specific heat Cp<0.6 g. cal/g. C.*
26. •Z. Zakrzewski, T. Fleisch, J. Pollak, M. Moisan, D. Guérin, M. Jasinski, D. Czylkowski, C. Larquet, A.L. Lesort, J.-C. Rostaing, " Système de couplage micro ondes - plasma et son

application à la destruction sélective de molécules chimiques" European application as EP 08305208.4 filed on 28 May 2008. Assignee: Air Liquide.

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28. M. Moisan, S. Moreau, M. Tabrizian, J. Pelletier, J. Barbeau, L'H. Yahia, "Système et procédé de stérilisation par plasma gazeux à basse température". European patent EP 1 181 062 (2004), validity: France, Belgium, Spain, Switzerland, Italy, Germany, UK., US 6 707 254 (2004) (restricted author list in the USA : M. Moisan, S. Moreau, M. Tabrizian, J. Pelletier). Assignee: Université de Montréal. *Early afterglow of a surface-wave sustained N₂-O₂ discharge as a means of filling a sterilization vessel ensuring bacterial spore inactivation by UV irradiation from the NO molecules generated from the combination of N and O atoms (first sterilization chamber concept).*
29. M. Moisan, N. Philip, B. Saoudi, "Système et procédé de haute performance pour la stérilisation par plasma gazeux à basse température", provisional Canadian application 2395659 (26/07/2002). PCT application filed on 24/07/2003, published on 5 February 2004 under WO2004/011039 A2. US patent 7 695 673. European patent EP 1 526 875, validity: Sweden, France, UK and Germany. Applicant: Université de Montréal. *Depending on the distance between the N₂-O₂ discharge and the sterilization chamber entrance, the sterilization chamber is filled with an early (flowing) afterglow (short distance) or a late afterglow (no ions present). UV biocidal irradiation action is maximized by adjusting the N₂/O₂ ratio (second sterilization plasma-vessel configuration).*
30. M. Moisan, B. Saoudi, J. Pollak, Z. Zakrzewski, "Procédé de stérilisation par plasma d'objets de nature diélectrique et comportant une partie creuse", provisional Canadian application 2412997 on 24 March 2003. PCT application (01/12/2003), published on 17 June 2004 as WO2004050128. European patent EP 1 567 200, validity France, UK and Germany. US patent application 2005 269199. Assignee: Université de Montréal. *Process for the plasma sterilization of dielectric objects comprising a hollow part, e.g. endoscope. The internal and external parts are sterilized sequentially using the N₂-O₂ discharge flowing afterglow.*
31. J. Pollak, M. Moisan, "Appareil et procédé d'inactivation et/ou stérilisation par plasma", US patent application 60/884,344 filed on 11 January 2007, PCT application: CA2008/000032 filed on 9 January 2008. US patent 8 277 727. Assignee: Université de Montréal. *A linear conducting strip is used to carry microwave field within and along a rectangular vessel in which bacterial spores to be inactivated are in direct contact with plasma.*
32. •Z. Zakrzewski, M. Moisan, D. Guérin, J.-C. Rostaing, "Dispositifs générateurs de plasmas micro-ondes et torches à plasma", French patent application FR0757719 on 20 September 2007. PCT application (16 September 2008), published under number WO 2009/047441 A1 on 16 April 2009 : 34 designated countries. US patent application publication as 2012/0018410 : Microwave plasma generating plasma and plasma torches. Assignee: Air

Liquide. *Plasma is generated by an EM field radiating from of a conductor (rod or micro-strip line surface), "attached" to a dielectric (the dielectric covers the conducting rod or substrate).*

33. •A. Mahfoudh, J. Séguin, M. Moisan, J. Barbeau, P. Levif, "Biocidal polymers, methods of preparation thereof, and methods for disinfecting and/or sterilizing objects", American provisional application 61/165,589 on first of April 2009.. PCT application WO 2010/111790 filed on April first 2010, published on 7 October 2010. US patent application: 200961165589. Assignee: Université de Montréal. *When pre-exposed to an ozone flow, some polymers determine a biocidal surface under a relative humidity atmosphere above 50 % as ozone is being slowly released.*
34. P. Levif, J. Séguin, M. Moisan, "Methods for plasma sterilization using packaging material" provisional US application 61/ 371429 on 6 August 2010, provisional PCT application WO2012/016329 A1 published on 9 February 2012. US patent 8,980,175. Assignee: Université de Montréal. *A process where plasma flowing afterglow sterilization is associated with non-porous packaging material to be sealed afterwards (infinite on shelf time).*
35. J. Pelletier, A. Lacoste, M. Moisan, "Gas discharge lamp, has casing comprising active gas containing oxygen and/or nitrogen oxide, where mixture of plasma gas and active gas emits UV or visible radiation and mercury content in casing is zero", French Patent FR 2 980 912. Assignee: CNRS and Université de Montréal. *Gaseous fluorescent-like lamps without mercury.*

Remarks:

- 1- Each entry ends, in italic font, with a sentence (that I wrote) summarizing the core of the invention.
- 2- Some patent applications were not pursued past the first examination report (none rejected) due either to lack of funds (UdeM) or, in the case of Air Liquide, for limiting expenses, making sure nonetheless that competition could not then patent an application that could prevent them from using a main patent: entries 16, 24, 25, 26 and 32 belong to that latter category.
- 3- The US Patent and Trade Office (USPTO) considers that, when a patent application describes a process and, additionally, a way of achieving it, it corresponds to two inventions and, therefore, should be identified by two distinct patent applications and, later on if the case, by two distinct patent numbers. This process is designated *a division of parent applications/patents*.
- 4- The order in which inventors appear in an application/patent is set, in principle, by the patent agent of the applicant. However, sometimes USPTO (and in Canada IC) modifies this order (why?).
- 5- Since 1995, patent validity (protection) is 20 years in all countries.

List of US patent applications (10) officially published by USPTO (disclosing patent content and drawings) and US patents granted (19).

US patent applied for: NO.	Title
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- 1 20140138361 Microwave plasma generating devices and plasma torches
 2 20120018410 Microwave Plasma Generating Plasma and Plasma Torches
 3 20110073282 Method for cooling microwave plasma and system for the selective destruction of chemical molecules using said method
 4 20100155222 Application of dense plasmas generated at atmospheric pressure for treating gas effluents. A division of the parent US application 20020195088.
 5 20090020009 Microwave plasma excitors
 6 20080234530 Gas conversion by chemical bond cleavage in an electric and-or magnetic field, e.g. for treatment of fluorinated effluents from semiconductor production, involves injecting gas into the field in a non-rectilinear manner
 7 200961165580 Biocidal polymers, methods of preparation thereof, and methods for disinfecting and/or sterilizing objects
 8 20080234530 Atmospheric Pressure Plasma Treatment of Gaseous Effluents
 9 20050269199 Process for the plasma sterilization of dielectric objects comprising a hollow part
 10 20040195088 Application of dense plasmas generated at atmospheric pressure for treating gas effluents

US patents granted

PAT. NO.	Title
1 <u>8,980,175</u>	<u>Methods for plasma sterilization using packaging material</u>
2 <u>8,277,727</u>	<u>Device and method for inactivation and/or sterilization using plasma</u>
3 <u>7,799,119</u>	<u>Microwave plasma excitors</u>
4 <u>7,695,673</u>	<u>Processes and devices for sterilizing contaminated objects</u>
5 <u>6,916,400</u>	<u>Device for the plasma treatment of gases</u>
6 <u>6,727,656</u>	<u>Power splitter for plasma device</u>
7 <u>6,707,254</u>	<u>Low temperature plasma sterilising system and method</u>
8 <u>6,541,917</u>	<u>Section of pipe for a gas treatment device and device incorporating such a section of pipe</u>
9 <u>6,298,806</u>	<u>Device for exciting a gas by a surface wave plasma</u>

- 10 [6,290,918](#) [Process and apparatus for the treatment of perfluorinated and hydrofluorocarbon gases for the purpose of destroying them](#) A division of the parent US patent 5,965,786
- 11 [6,224,836](#) [Device for exciting a gas by a surface wave plasma and gas treatment apparatus incorporating such a device](#)
- 12 [6,190,510](#) [Process for purifying a gas and apparatus for the implementation of such a process](#)
A division of the parent US patent 5,993,612
- 13 [5,993,612](#) [Process for purifying a gas and apparatus for the implementation of such a process](#)
- 14 [5,965,786](#) [Process and apparatus for the treatment of perfluorinated and hydrofluorocarbon gases for the purpose of destroying them](#)
- 15 [5,759,623](#) [Method for producing a high adhesion thin film of diamond on a Fe-based substrate](#)
- 16 [5,360,485](#) [Apparatus for diamond deposition by microwave plasma-assisted CVD](#)
- 17 [4,906,898](#) [Surface wave launchers to produce plasma columns and means for producing plasma of different shapes](#) A division of the parent US patent 4,810,933.
- 18 [4,810,933](#) [Surface wave launchers to produce plasma columns and means for producing plasma of different shapes](#)
- 19 [4,049,940](#) [Devices and methods of using HF waves to energize a column of gas enclosed in an insulating casing](#)
-

From Air Liquide 2008 annual report, following a share holder question, comments made by Mr. Thierry Sueur, V-P Head of Air Liquide Intellectual Property:

Share holder question: "Can you cite a recently registered patent that makes an important contribution to sustainable development"? Answer: "The Universal Plasma Abatement System (UPAS) is an undeniably prominent invention. It meets environmental challenges posed by the semiconductor industry, where production methods require the use of gases that can harm the environment. Thanks to this plasma-based technology which destroys these gases, the environmental impact in this process is now under control".

- [6,290,918](#) [Process and apparatus for the treatment of perfluorinated and hydrofluorocarbon gases for the purpose of destroying them](#) A division of US parent patent 5,965,786
- [5,965,786](#) [Process and apparatus for the treatment of perfluorinated and hydrofluorocarbon gases for the purpose of destroying them.](#)

M. Sc. and Ph. D graduated students

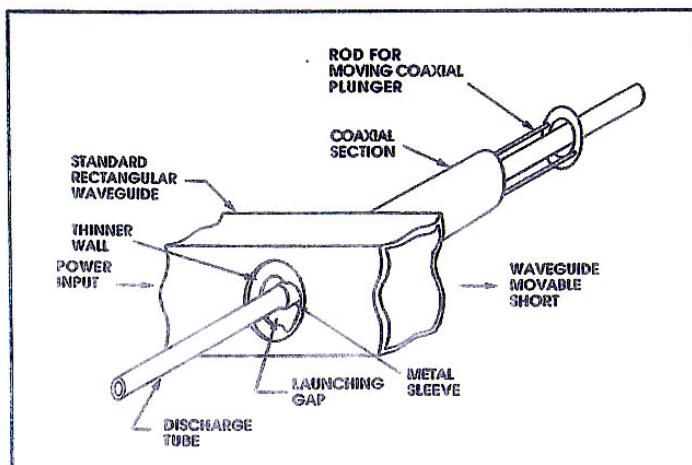
- Gary MITCHEL (M. Sc.), Le surfaguide, une nouvelle source de longues colonnes de plasma H.F. (mars 1976).
- Christopher MOUTOULAS (M. Sc.), Réalisation et étude du gain d'un laser He-Ne pompé par une décharge microonde d'ondes de surface (juin 1985).
- Gaston SAUVÉ (M. Sc.), Effet de la fréquence d'excitation d'un plasma d'ondes de surface sur la gravure du polyimide (octobre 1988).
- Claude BARBEAU (M. Sc.), Étude expérimentale du bilan énergétique d'une décharge entretenue par une onde de surface (octobre 1988).
- Joëlle MARGOT (D. Sc.), Étude théorique et expérimentale des plasmas de grand diamètre entretenus par une onde électromagnétique de surface de haute fréquence se propageant sur le mode à symétrie, soit azimutale, soit dipolaire (juillet 1989). - Codirection avec A. Ricard (thèse soutenue à Paris-XI).
- Richard CLAUDE (Ph. D.), Polymérisation par plasma: effet de la fréquence de l'onde électromagnétique entretenant la décharge (juin 1990). - Codirection avec M.R. Wertheimer.
- Serge LEVESQUE (M. Sc.), Étude de l'effet de fréquence sur les caractéristiques d'un plasma entretenu par une onde de surface à des pressions voisines de l'atmosphère (octobre 1991).
- Fouad BOUNASRI (M. Sc.), Effets de la tension et de la fréquence de polarisation du substrat sur la vitesse de gravure par plasma du polyimide (février 1992).
- Louis ST-ONGE (M. Sc.), Caractérisation de décharges d'hydrogène entretenues par un champ de haute fréquence (40-2450 MHz) et optimisation de leur rendement en hydrogène atomique (novembre 1992).
- Iscra BOYADJIÉVA (M. Sc.), Laser CO₂ en guide d'ondes à excitation par ondes de surface électromagnétiques: étude expérimentale (décembre 1992).
- Carlos DE MELLO BORGES (Ph. D.), Élaboration de couches minces de diamant à partir d'un plasma d'onde de surface non conventionnel (juin 1996).
- Fouad BOUNASRI (Ph. D.), Étude de la gravure du tungstène, du silicium, du carbure de silicium et d'une résine en fonction de la température du substrat dans un magnétoplasma à onde de surface (juin 1996). – Codirection avec M. Chaker.
- Patrice JONES (M. Sc.), Destruction de gaz moléculaires à effet de serre au moyen d'un plasma micro-ondes fonctionnant à la pression atmosphérique (juin 1996).
- Céline CAMPILLO (M. Sc.), Dépôt et caractérisation de couches de diamant polycristallin sur du carbure de tungstène cémenté au cobalt (WC-Co) (mars 1999).
- Stéphane MOREAU (M. Sc.), Stérilisation par plasma différé : compréhension et optimisation du procédé (février 2000).
- Philippe MÉREL (Ph. D.), Conception et mise au point d'un système combinant l'ablation laser et une source d'azote atomique pour la synthèse de nitrides (CN_x et GaN) sous la forme de couches minces (avril 2001). Codirection avec M. Chaker.

- Yassine KABOUIZI (Ph. D.), Contraction et filamentation des décharges micro-ondes entretenues à la pression atmosphérique : application à la détoxication des gaz à effet de serre (juin 2003).
- Marie-Charlotte CREVIER (M. Sc.), Effets de la stérilisation par plasma N₂-O₂ en post-décharge sur des spores de *B. subtilis* et surface de bio-polymères (juin 2003). Codirection avec L'H Yahia.
- Nicolas PHILIP (M. Sc.), Stérilisation à basse température et à pression réduite en post-décharge de plasma: étude et analyse du rôle des UV dans l'inactivation de spores bactériennes (juin 2003). Codirection avec J. Barbeau.
- Eduardo CASTAÑOS-MARTINEZ (M. Sc.), Influence de la fréquence d'excitation des décharges entretenues par onde de surface sur la contraction et la filamentation à la pression atmosphérique (mars 2005).
- Jérôme POLLAK (M. Sc.), Applicateurs linéaires de champs EM utilisant la technologie triplaqué pour l'entretien de décharges HF (50-2450 MHz) (août 2005).
- Thomas FLEISCH (M. Sc.), Adaptation d'impédance des applicateurs de champ HF servant à l'entretien de plasmas d'onde de surface (mars 2006).
- Crina Anca POPOVICI (M. Sc.), Caractérisation de la post-décharge à pression réduite d'un plasma de N₂-O₂ : optimisation des conditions opératoires et maximisation de l'intensité UV émise dans la chambre de stérilisation. Application de la loi de fluence à l'inactivation de spores bactériennes par les photons UV (mai 2006).
- Martin NANTEL-VALIQUETTE (M. Sc.) Destruction de gaz à effet de serre par un plasma micro-ondes entretenu à la pression atmosphérique (mars 2007).
- Mustafa-Karim BENHACENE-BOUDAM (Ph.D.) Contribution à l'étude de l'inactivation de micro-organismes par plasma (novembre 2007).
- Jérôme POLLAK (Ph.D.) Développement et utilisation de sources de plasma pour stériliser des instruments médicaux (février 2009).
- Ahlem MAHFOUDH (Ph. D.) Étude des mécanismes d'inactivation des microorganismes suite à un traitement à l'ozone (décembre 2009).
- Eduardo CASTAÑOS-MARTINEZ (Ph. D.) Contraction et décontraction des décharges micro-ondes entretenues à la pression atmosphérique (novembre 2010).
- Denis CARIGNAN (M. Sc.) Étude de l'influence de la réassociation en surface des atomes N et O sur l'inactivation de spores bactériennes dans une post-décharge N₂-%O₂ basse pression en flux (février 2013).
- Amaury KILICASLAN (M. Sc.) Étude spectroscopique d'un plasma micro-onde à la pression atmosphérique et son application à la synthèse de nanostructures (août 2013).

Post-doctoral students (18)

HIGH DENSITY PLASMA SOURCES

Design, Physics and Performance



Edited by
Oleg A. Popov

NOYES PUBLICATIONS

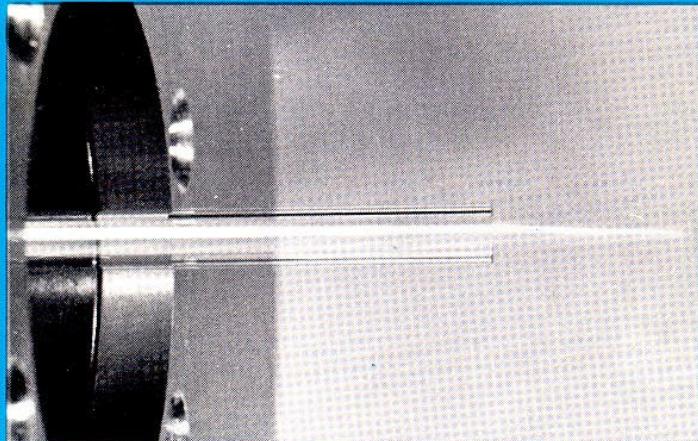
Schéma du surfatron-guide

Waveguide – surfatron schematic description

The Journal of **Microwave Power**

Volume 14, No. 1, March 1979

THE INTERNATIONAL MICROWAVE APPLICATIONS
JOURNAL DEVOTED TO THE INDUSTRIAL, SCIENTIFIC,
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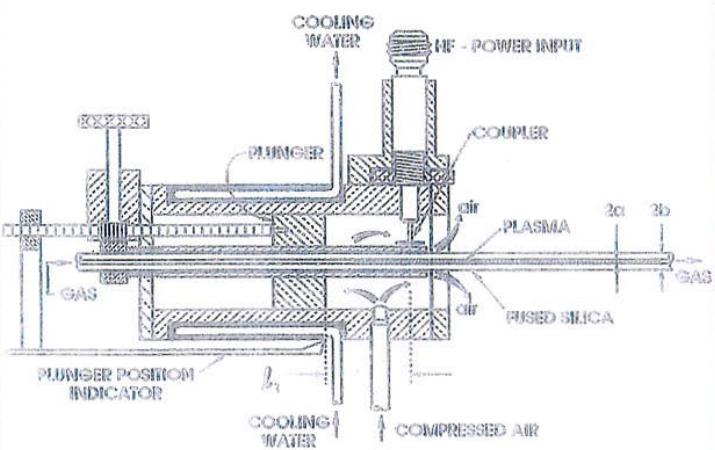
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Schéma du surfatron

Vide

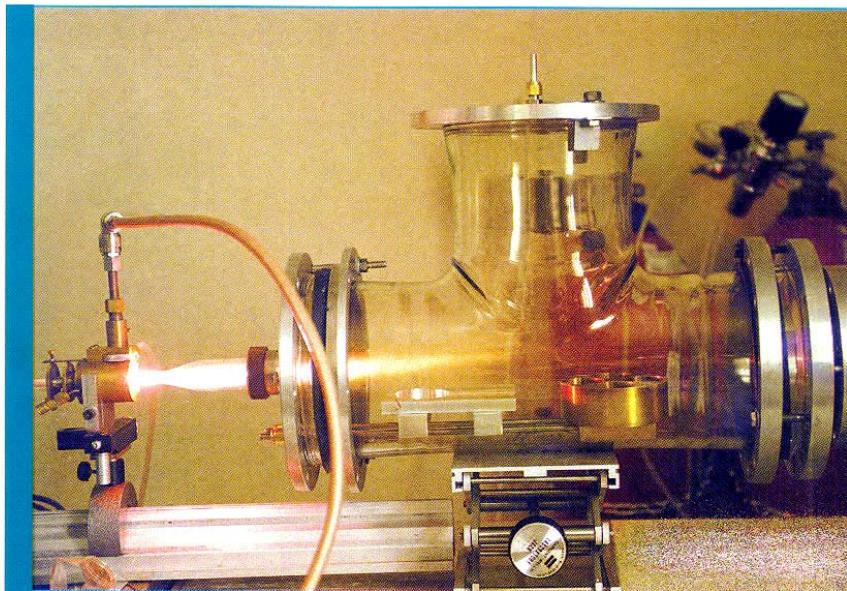
science, technique et applications

56ème année

N°299

Volume 1/4

2001



"Réacteur à plasma pour la stérilisation" - Photo de Bernard Lambert / Laboratoire de Michel Moisan, Université de Montréal.

Stérilisation - Plasmas froids

sfrv

First surface-wave plasma reactor, which was instrumental in understanding plasma sterilization
(Groupe de physique des plasmas, Université de Montréal)

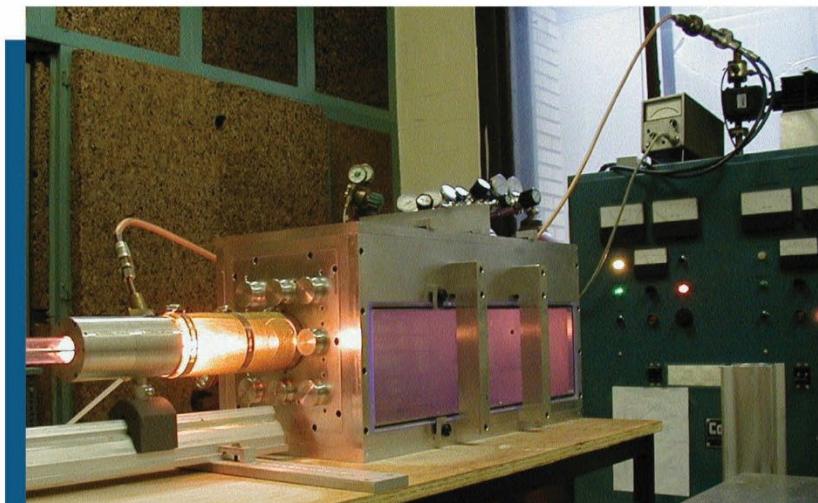
Vide

science, technique et applications

303 Le Vide : science, technique et applications

"Procédés plasmas froids - Stérilisation médicale & alimentaire" 1/4 2002

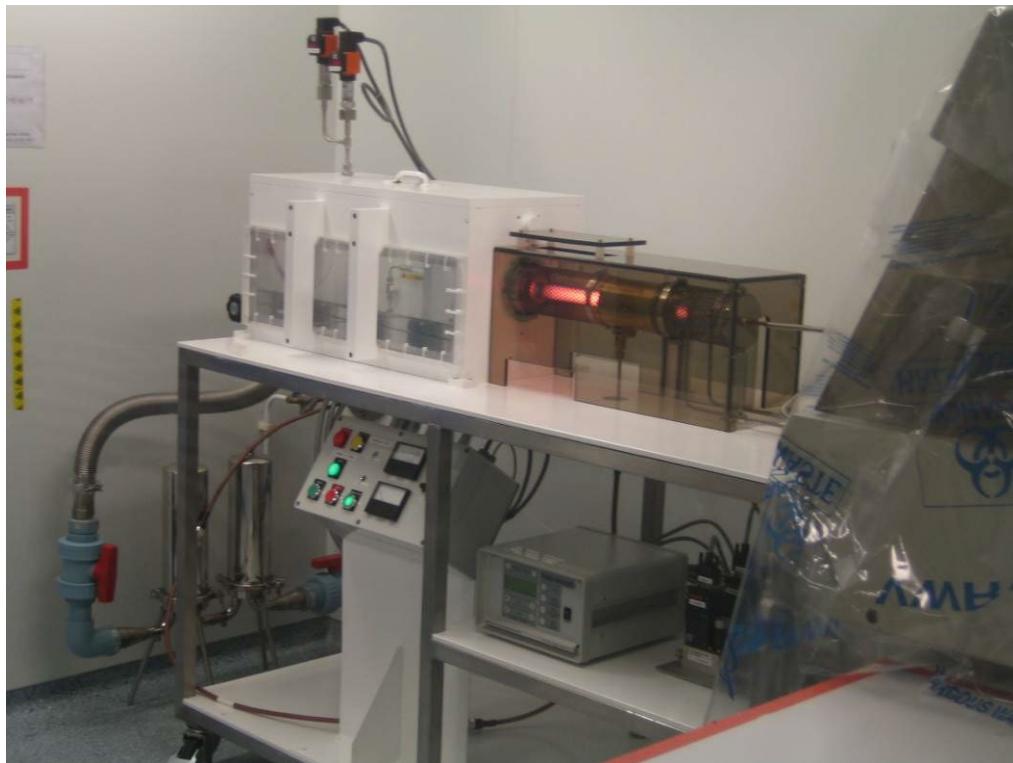
57ème année
N° 303
Volume 1/4
2002



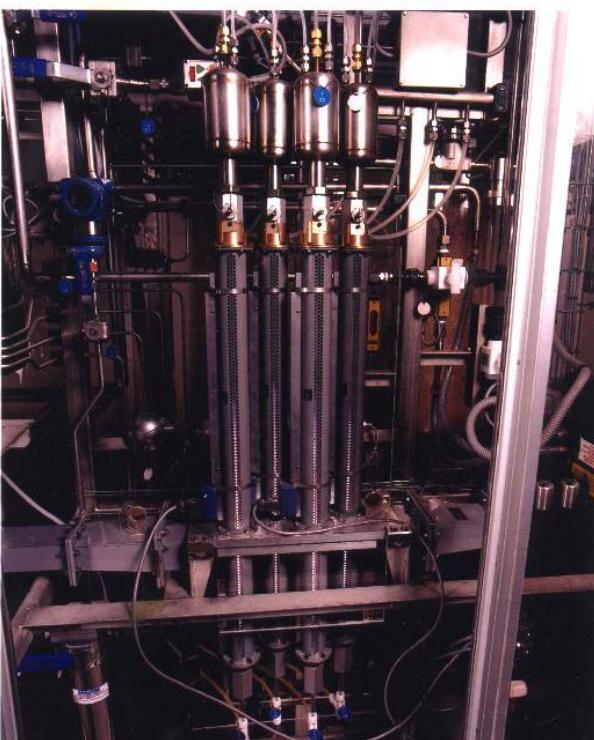
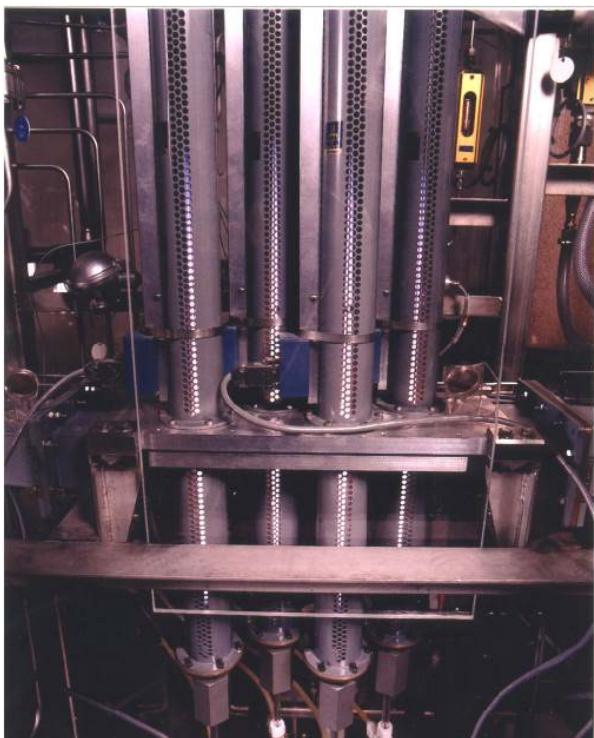
Chambre de stérilisation de 50 litres en régime de post-décharge à 915 MHz (Université de Montréal).
Photo : Nicolas Philip

Procédés plasmas froids Stérilisations médicale & alimentaire

sfr



Sterilization system designed and realized by Moisan's team, implemented at the Centre Hospitalier Universitaire (CHU) in Liège, Belgium where it was installed by Air Liquide plasma physics engineering group (CRDP, Versailles, France). The experiments, conducted by Dr. W. Zorzi (CHU Liège), aimed at investigating the inactivation of the pathogenic Prion protein (mad cow disease) by the late flowing-afterglow(meaning no electrons left) of a N₂-O₂ discharge sustained by a propagating EM surface wave. Work performed in a P3 biological safety level environment.





First automated system, installed at Moissy-Cramayel (France) for ensuring Kr and Xe very high-level purification. A whole factory building is now dedicated to such rare gas purification and the process is fully computer-control, working 24/24. A similar factory has been put up in Germany.



First Air Liquide prototype assembled to eliminate green-house gases currently used in micro-electronics fabs (chips manufacturing), built according to Moisan's team indications.



More advanced greenhouse gases remediation system commercialized under UPAS (Universal Plasma Abatement System) by Air Liquide company for microelectronics fabs at different locations in the world. It can handle up to 4 production plasma reactors (total gas flow up to 120 slm). Maximum MW power consumption 6 kW. From left to right, system computer controlled, surfaguide plasma abatement system, alkaline-bed unit for collecting process residue (scrubber).

Still more compact UPAS system (not shown) are now being commercialized: proprietary information.