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# OVERVIEW ON STUDIES OF MARTIAN LIKE CO<sub>2</sub>-N<sub>2</sub> MIXTURE BY INDUCTIVELY COUPLED PLASMA TORCH

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## ABSTRACT

The purpose of the work is to make an overview on the results obtained through the studies on martian plasmas created by inductively coupled plasma torches (ICP). As the main advantage of the ICP torch is the absence of electrode compared to the others various test facilities, the radiative properties of this kind of plasmas are of interest to propose test cases in order to validate radiation models. ICP torches can work under various operating conditions in terms of pressure, enthalpy or flow. As a consequence, the studied plasma can be either at thermodynamical equilibrium or out of equilibrium, without problems of stability in time. The presentation concerns only the plasmas formed with a martian like CO<sub>2</sub>-N<sub>2</sub> mixture and all the parameters of test facilities will be precised.

The following paper corresponds to the first step of a global paper which will be proposed later and it reports only the oral presentation which has been done during the third International Workshop of RHTG.

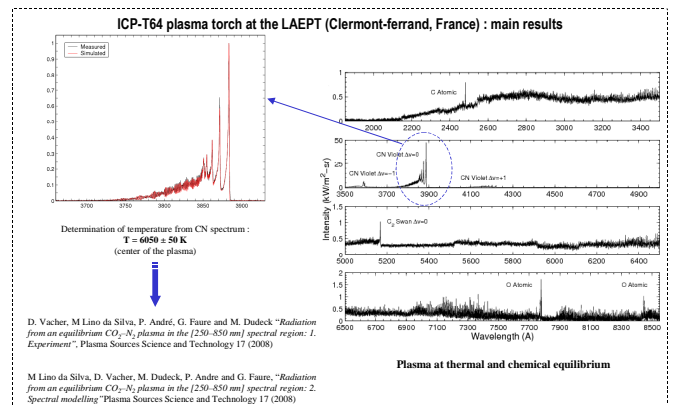
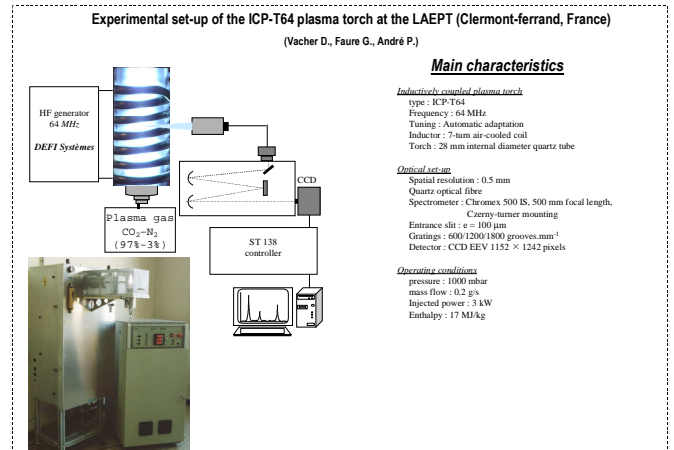
## 1. INTRODUCTION

Five laboratories have been found concerning the study of CO<sub>2</sub> or CO<sub>2</sub>-N<sub>2</sub> plasmas by inductively coupled plasma torch. The laboratories which are about to start this kind of study do not appear in this presentation.

The laboratories which have obtained results are the following :

- L.A.E.P.T. (Laboratory of Electrical Arc and Thermal Plasmas) located in Clermont-Ferrand, France;
- C.O.R.I.A. (Complexe de Recherche Interprofessionnel en Aérothermochimie) located at Rouen, France;
- I.R.S. (Institut für RaumfahrtSysteme) located at Stuttgart, Germany;
- V.K.I. (Von Karman Institute) located at Rhode Saint Genese, Belgium;
- I.P.M. (Institute for Problems of Mechanics) located at Moscow, Russia.

## 2. L.A.E.P.T. (Clermont-Ferrand, France)



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1. D.Vacher, M. Lino da Silva, P. André, G. Faure and M. Dudeck (2008) *Radiation from an equilibrium CO<sub>2</sub>-N<sub>2</sub> plasma in the [250-850 nm] spectral region: 1. Experiment* Plasma Sources Science and Technology 17 (2008) 035012 (8pp)
2. M. Lino da Silva, D. Vacher, M. Dudeck, P. André and G. Faure (2008) *Radiation from an equilibrium CO<sub>2</sub>-N<sub>2</sub> plasma in the [250-850 nm] spectral region: 2. Spectral modelling* Plasma Sources Science and Technology 17 (2008) 035013 (9pp)
3. M. Lino de Silva, *An adaptative Line-by-Line-Statistical Model for Fast and Accurate Spectral Simulations in Low-Pressure Plasmas* JQSRT, Vol. 108, n°1, pp. 106-125

### 3. C.O.R.I.A. (Rouen, France)

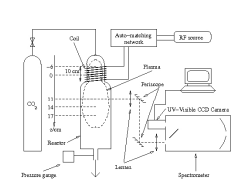
**ICP torch at the CORIA (Rouen, France) : (1)**  
(Rond C, Bultel A, Boubert P., Chéron B.G.)

**Main characteristics**

Inductively coupled plasma torch  
 Frequency: 13.56 MHz  
 Inductor: 7 turns water-cooled coil  
 Torch: 60 mm (coil location)  
 90 mm (downstream)

Optical set-up  
 spectroscopy system  
 Spectrometer: SpectraPro-300L  
 Entrance slit:  $e = 50 \mu\text{m}$   
 Gratings: 1200 grooves/mm<sup>2</sup> (blazed at 300 nm)  
 Detector: ICCD camera PI-Max (Princeton)

Operating conditions  
 pressure: 1-2 mbar  
 flow rate: 0.1 - 0.3 dm<sup>3</sup>/min  
 Max. injected power: 2 kW  
 Power delivered to the plasma: 80-160 W  
 Specific enthalpy: 13.4 - 40.8 MJ/kg

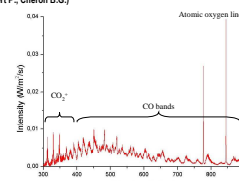


This experimental set-up has been presented by A. Bultel :  
 - Spatial evolution of the radiation from a non equilibrium CO<sub>2</sub> RF plasma.

**ICP torch at the CORIA (Rouen, France) (1) : main results**  
(Rond C, Bultel A, Boubert P., Chéron B.G.)

**Aim of the study :**

- to analyse the CO<sub>2</sub> dissociation at low pressure
- to calculate CO-O chemiluminescent emission
- to investigate the evolution of the plasma chemistry from the creation zone to downstream
- to estimate the CO and O densities in their ground state and their excited ones



**Plasma under thermal and chemical nonequilibrium**

	T <sub>g</sub> (K)	T <sub>e</sub> (K)	T <sub>ex</sub> (K)	density of the upper state (m <sup>-3</sup> )
Triplet (O <sup>3</sup> P <sub>2</sub> → a <sup>1</sup> P <sub>1</sub> )	500	1000	5000	10 <sup>17</sup>
Assand (a <sup>1</sup> P <sub>2</sub> → a <sup>1</sup> P <sub>1</sub> )	500	7000	5000	10 <sup>14</sup>

Estimation of temperatures from CO system in the post discharge

**ICP torch at the CORIA (Rouen, France) : (2)**  
(Boubert P.)

**Main characteristics**

Inductively coupled plasma torch  
 Frequency: 176 MHz  
 Inductor: 5 coils  
 Torch: 100 mm diameter quartz tube

Optical set-up  
 Spectrometer: Sopra1500  
 Entrance slit:  $e = 7 \mu\text{m}$   
 Gratings: 2400 grooves/mm<sup>2</sup> (blazed at 400 nm)  
 Detector: Photodiode array (Thorn TH821)

Operating conditions  
 pressure: 20 mbar  
 flow rate: 18 L/min  
 injected power: 25 kW  
 specific enthalpy: 7 MJ/kg  
 plasma gas: CO<sub>2</sub>-N<sub>2</sub>-Ar (95%-3%-2%)

**Conclusion of the study :**

- CN : good accuracy experiment theory
- C<sub>2</sub> : notable differences between experiment and theory  
 strong perturbations of static  
 anomalies of states population

Violet system of CN	T <sub>g</sub> (K)	ΔT <sub>ex</sub> (K)	T <sub>ex</sub> (K)	ΔT <sub>ex</sub> (K)
FWHM = 0.06 nm	8000	500	10000	200
FWHM = 0.08 nm	8000	500	10000	200

C <sub>2</sub> system	T <sub>g</sub> (K)	ΔT <sub>ex</sub> (K)	T <sub>ex</sub> (K)	ΔT <sub>ex</sub> (K)
FWHM = 0.075 nm	9000	1000	10000	1000

Estimation of temperatures

### REFERENCES

1. C. Rond, A. Bultel, P. Boubert, B.G. Chéron *Spectroscopy measurements of nonequilibrium CO<sub>2</sub> plasma in RF torch*, submitted to Chemical Physics (2008)
2. P. Boubert, P. Vervisch (2008) *CN spectroscopy and physico-chemistry in the boundary layer of a C/SiC tile in a low pressure nitrogen/carbon dioxide plasma flow*, Chemical Physics, Vol. 112, n°23, pp. 10482-10490
3. P. Boubert (1999) *Méthodes spectroscopiques appliqués aux plasmas et aux milieux à hautes enthalpies*, PhD Thesis, University of Rouen

### 4. I.R.S. (Stuttgart, Germany)

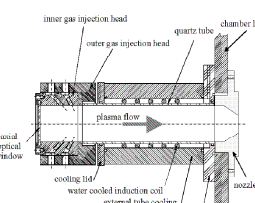

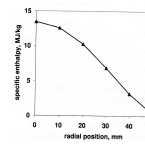
**ICP torch at the IRS (Stuttgart, Germany)**  
(Herdrich G., Endlich P. and al.)

**Main characteristics**

Inductively heated generator IPG4  
 Frequency: 0.6 MHz  
 Inductor: 5 turns water-cooled coil  
 Torch: 84mm internal diameter quartz tube  
 Nozzle throat diameter: 50 mm

Optical set-up  
 mini-Spectrometer:  
 Entrance slit:  $e = 7 \mu\text{m}$   
 Gratings: 1  
 Detector: 2000 pixel detector (pixel resolution: 0.3 nm)

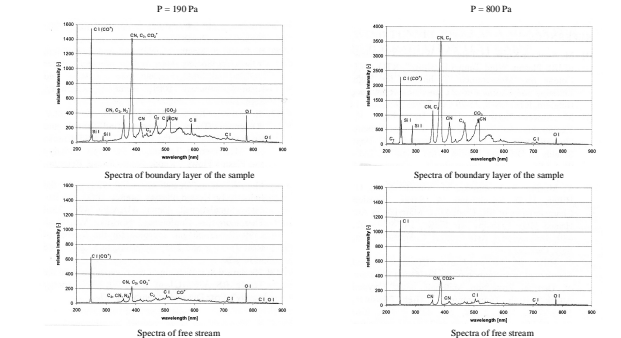
Operating conditions  
 pressure: 1.9-8 mbar  
 CO<sub>2</sub> mass flow: 3.7 g.s<sup>-1</sup>  
 N<sub>2</sub> mass flow: 70 m.g.s<sup>-1</sup>  
 Thermal plasma power: 20 kW

**Measurements in the plasma :**

- Heat flux
- Pitot pressure
- Thermal plasma power (calorimeter)
- Study of the influence of dust particles (injection of iron oxides and silicon dioxides with  $\phi < 10 \mu\text{m}$ )

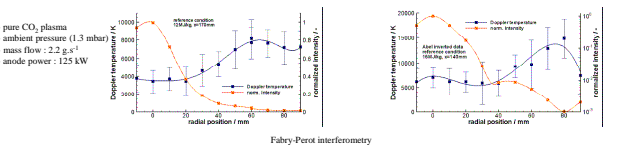
**ICP torch at the IRS (Stuttgart, Germany) : Example of spectra**  
(Herdrich G., Endlich P. and al.)



No values of the estimated temperatures of plasma

**ICP torch at the IRS (Stuttgart, Germany) : First estimation of temperatures**  
(Lein S., Herdrich G. and al.)

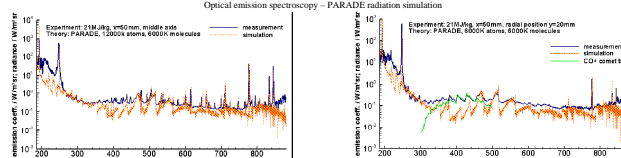
The results are issued from a poster presented in the 6<sup>th</sup> International Planetary Probe workshop (2008)  
 - Characterization of CO<sub>2</sub> plasma free stream conditions for atmospheric entry simulation \*



pure CO<sub>2</sub> plasma  
 ambient pressure: (1.3 mbar)  
 mass flow: 2.2 g.s<sup>-1</sup>  
 mode power: 125 kW

Fabry-Pérot interferometry

Optical emission spectroscopy - PARADE radiation simulation



Final Conclusion : disagreement theory-experimental data (quantitatively not qualitatively)

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2. G. Herdrich, M. Auweter-Kurtz, P. Endlich, *Mars Entry Simulation using the Inductively Heated Plasma Generator IPG4*, Engineering Note *Journal of Spacecrafts and Rockets* Vol. 40, No. 5, pp. 690-694, Sept.-Oct. 2003

3. P. Endlich, M. Auweter-Kurtz, G. Herdrich, *Mars Entry Simulation with Dust Using an Inductively Heated Generator*, Paper AIAA-2002-3237, 22<sup>nd</sup> AIAA Aerodynamic Measurement Technology and Ground Testing Conference, St. Louis, MI, USA, 24-26 June 2002

4. G. Herdrich, M. Auweter-Kurtz, P. Endlich, T. Laux, *Simulation of Atmospheric Entry Manoeuvres using the Inductively Heated Plasma Wind Tunnel PWK3*, DGLR Jahrestagung, DGLR-JT2002-254 Stuttgart, Germany, September 2002

5. G. Herdrich, M. Auweter-Kurtz, P. Endlich, T. Laux, *Simulation of Atmospheric Entry Manoeuvres using the Inductively Heated Plasma Wind Tunnel PWK3*, DGLR Jahrestagung, DGLR-JT2002-254 Stuttgart, Germany, September 2002

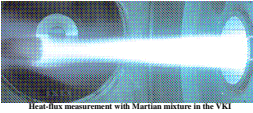
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7. G. Herdrich, S. Löhle, M. Auweter-Kurtz, P. Endlich, M. Fertig, S. Pidan, *IRS Ground-Testing Facilities: Thermal Protection System Development, Code validation and Flight Experiment Development*, Paper AIAA 2004-2596, 24<sup>th</sup> AIAA Aerodynamic Measurement Technology and ground Testing Conference, Portland, Oregon, USA, June/July 2004

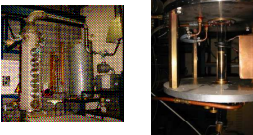
### 5. V.K.I. (Rhode Saint Genese, Belgium)

**ICP torch at the VKI (Rhode Saint Genese, Belgium)**  
(Chazot O., Carbonaro M. and al.)

	Plasmatrix	Minitech
Frequency (MHz)	1.16	1.5
Power (kW)	1200	15
Operating pressure	1-12 mbar	Martian atmosphere
Inductor	3	2
coiled (d=4mm)	water	water
external diameter tube (mm)	80-140	250
Internal diameter (mm)	150	175
Flow rate	0.50	1.00
Embassy	0.050 m/s	1.00



Heat-flux measurement with Martian mixture in the VKI Plasmatron



Overview of the minitech

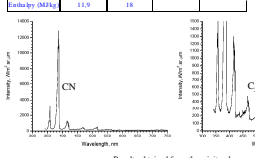
**Available instrumentation:**

- cooled pressure and heat fluxes probes
- Langmuir probes
- Laser Doppler velocimeter
- One meter emission spectrometer with CCD camera
- two color pyrometer
- Laser spectroscopy techniques (TALIF)
- (Two photon Absorption Laser Induced Fluorescence)

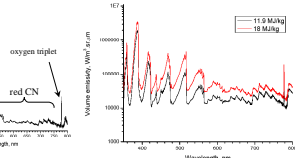
**ICP torch at the VKI (Rhode Saint Genese, Belgium)**  
(Playez M. and al.) [TRP-ESA]

	test1	test2	test3	test4
Power (kW)	15	30	3.2	3.2
Pressure (mbar)	8	8	10	7.5
Flow rate	CO <sub>2</sub> (97%) - N <sub>2</sub> (3%) (3000 l/min)			
Mass flow (g/s)	8	8	0.51	0.51
Embassy (M/s)	11.6	18		

**Optical setup:**  
Spectrometer: Ocean Optics HR4000CG-LV-NIR;  
Wavelength interval: 200-1400 nm  
Entrance slit:  $\tau = 5 \mu\text{m}$   
Gratings: 300 grooves/mm<sup>2</sup>  
Detector: 3648-elements linear silicon CCD array

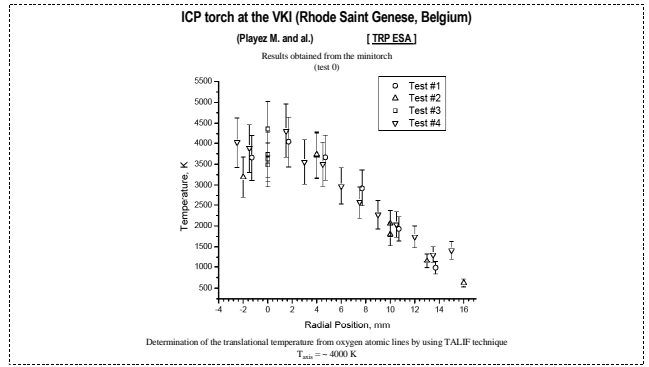


Results obtained from the minitech (test 1)



Results obtained from the plasmatron (test 1-2)

**Difficulty of interpretation - fluctuations of the jet**



### REFERENCES

The informations are given by M. Playez.

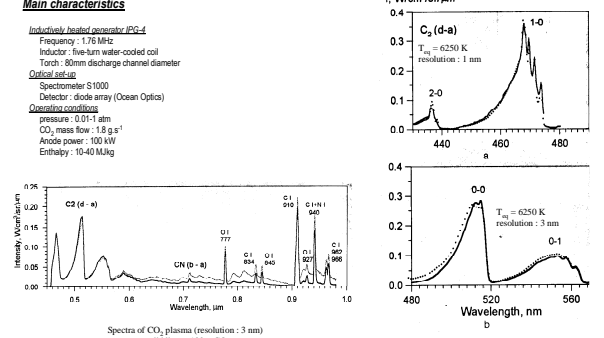
### 6. I.P.M. (Moscow, Russia)

**ICP torch at the IPM (Moscow, Russia)**  
(Baronets P.N., Bykova N.G. and al.)

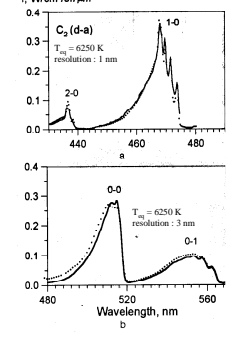
**Main characteristics**  
Inductively heated generator IIG-4  
Frequency: 1.16 MHz  
Inductor: five-turn water-cooled coil  
Torch: 80mm discharge channel diameter

**Optical setup**  
Spectrometer: S1000  
Detector: diode array (Ocean Optics)

**Operating conditions**  
pressure: 0.05-1 atm  
CO<sub>2</sub> mass flow: 1.8 g/s<sup>1</sup>  
Anode power: 100 kW  
Embassy: 10-40 M/s



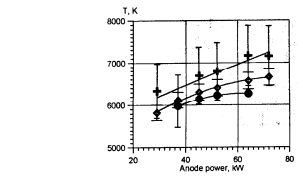
Spectra of CO<sub>2</sub> plasma (resolution: 3 nm)  
- solid lines: 100% CO<sub>2</sub>  
- dotted line: CO<sub>2</sub> + 3% N<sub>2</sub> + (0-10%) Ar



Correlation of C<sub>2</sub> Swan system band head.  
dotted line: experimental spectrum  
solid line: calculated spectrum

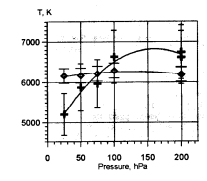
**ICP torch at the IPM (Moscow, Russia)**  
(Baronets P.N., Bykova N.G. and al., 1998)

**Plasma temperature measurements by optical methods**



Plasma temperature for pressure 0.1 atm (oxygen, carbon lines plus C<sub>2</sub> molecular bands)

- RI values, averaged of 2 OI lines pairs
- AI values, averaged over three oxygen and four carbon lines
- Values from C<sub>2</sub> molecular bands

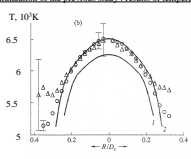


Plasma temperature for anode power 45 kW

Legend:  
- Absolute Intensity (AI) and Relative Intensity (RI) methods for atomic spectral lines  
- Emission of the C<sub>2</sub> molecule

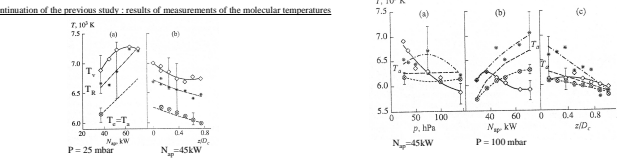
**ICP torch at the IPM (Moscow, Russia)**  
(Bykova N.G., Kuznetsova L.A., 2004)

**Continuation of the previous study - results of temperature measurements from atomic lines**

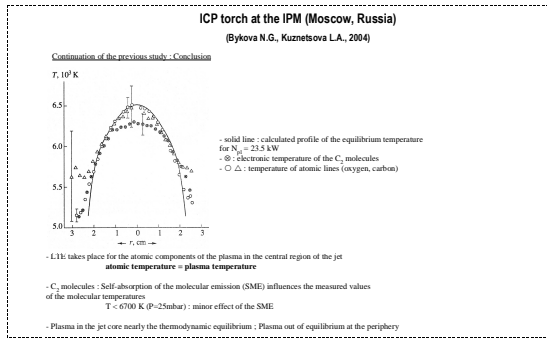


Radial profiles of the atomic temperature of a CO<sub>2</sub> plasma:  
- N<sub>0</sub> = 45 kW  
- P = 100 mbar  
solid line (1): calculated equilibrium temperature for N<sub>0</sub> = 19 kW  
solid line (2): calculated equilibrium temperature for N<sub>0</sub> = 23.5 kW

**Continuation of the previous study - results of measurements of the molecular temperature**



Influence of the self-absorption of molecular emission (C<sub>2</sub>, I)



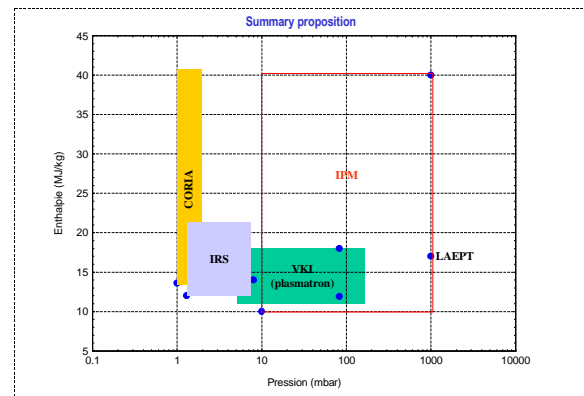
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## 7. CONCLUSION

A conclusion can not be done due to the fact that each laboratory works under different conditions in terms of flow, injected power, operating frequency and operating pressure. However, it is very interesting to gather all the data in order the domain of applications of each laboratory and also in order to create a connection between all these laboratories.

The following figure propose a regrouping of the data of each laboratory in terms of specific enthalpy and pressure. Of course, The field of investigation of each laboratories is likely to evolve.



## ACKNOWLEDGMENTS

I would like to thank all the colleagues who permitted to this presentation to exist. I express all my recognition to them and thanks once again them for all the informations that they sent to me. These colleagues are : P. Boubert, A. Bultel, G. Herdrich, A.F. Kolesnikov, M. Playez and C. Rond.

I wish that the discussion will continue in order to still work together on the atmospheric entries with inductively coupled plasma torches.