NON-LINEAR PHENOMENA IN DUSTY PLASMAS: MIXED-MODE OSCILLATIONS

M. Mikikian

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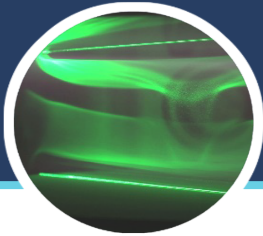
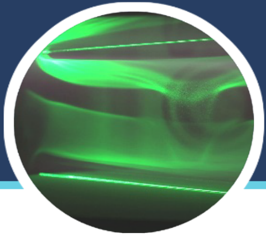


OUTLINE

- ❑ **Dusty (or complex) plasmas?**
- ❑ **Nanoparticle formation in a few words …**
- ❑ **Experimental setup**
- ❑ **The "void"**
- ❑ **Void instabilities: Heartbeat**
- ❑ **Last beats: Mixed-Mode Oscillations**



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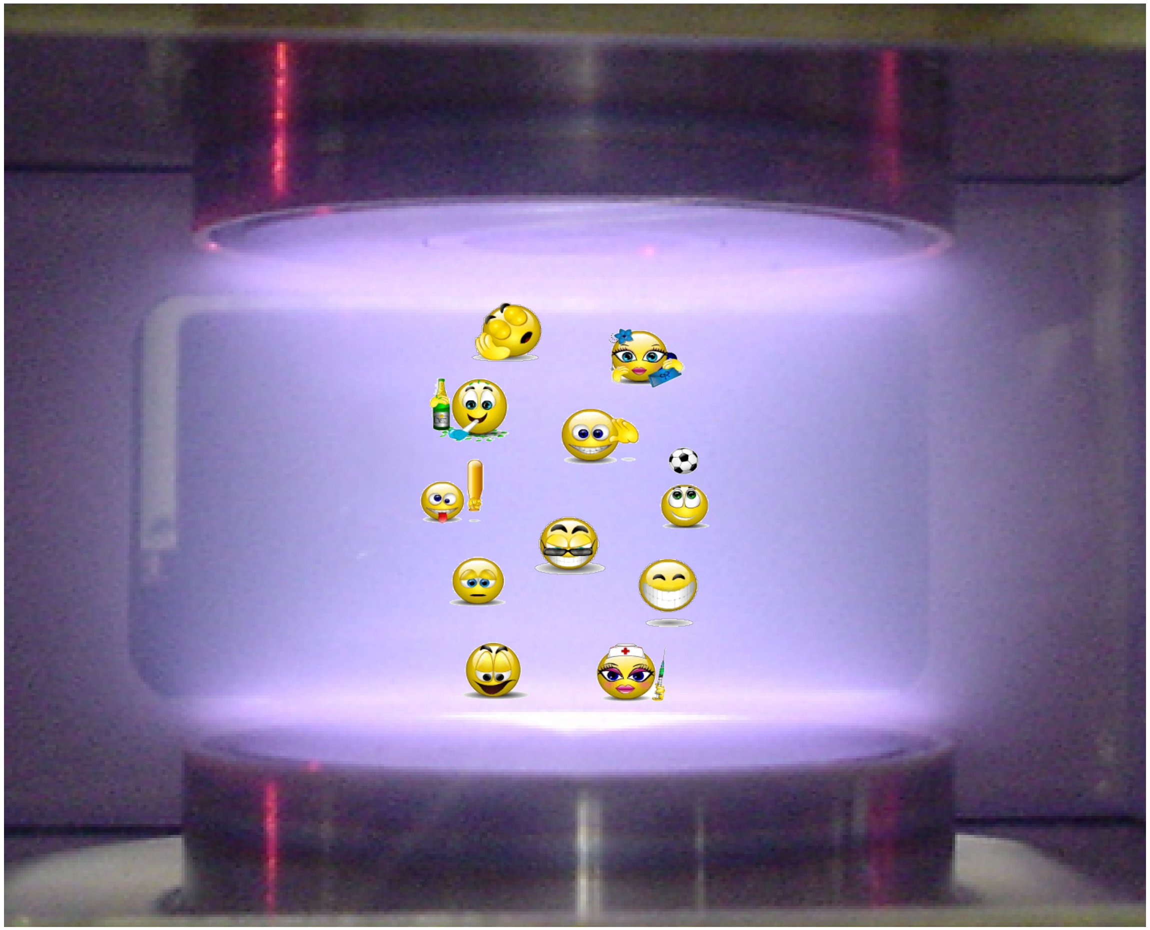
DUSTY (OR COMPLEX) PLASMAS?

Plasma = electrons, ions, neutral atoms, molecules
Dust particles, nanoparticules = solid bodies from a few nm to cm



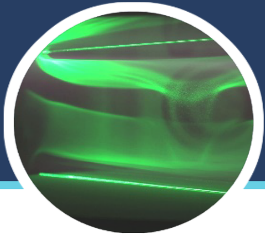
Multicomponent systems

Colloids, Granular media

New charged species in the plasma

$$n_i = n_e + Z_d n_d$$

→ Modifications of plasma properties



DUSTY (OR COMPLEX) PLASMAS?

Presence of reactive gases

SiH_4, CH_4, C_2H_2

→ Succession of chemical and physical reactions

Material sputtering

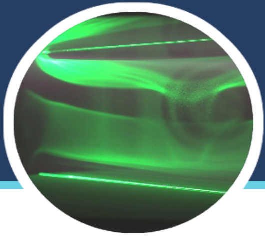
Tungsten, Graphite, …

All surfaces exposed to a plasma can be sputtered

Mainly by ion bombardment

Injection

To study dusty (complex) plasmas, many experiments are performed by injecting manufactured (calibrated) dust particles

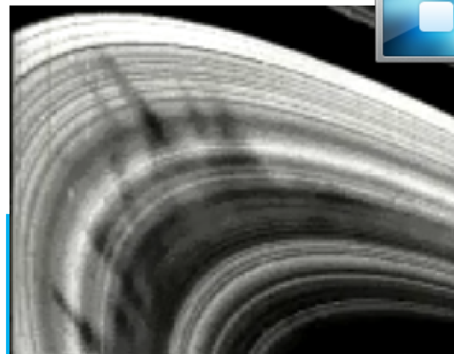


DUSTY (OR COMPLEX) PLASMAS?

In nature

In astrophysics

- Comets
- Planetary rings



for ex. C.K. Goertz Rev. Geophys. (1989)

DUSTY (OR COMPLEX) PLASMAS?

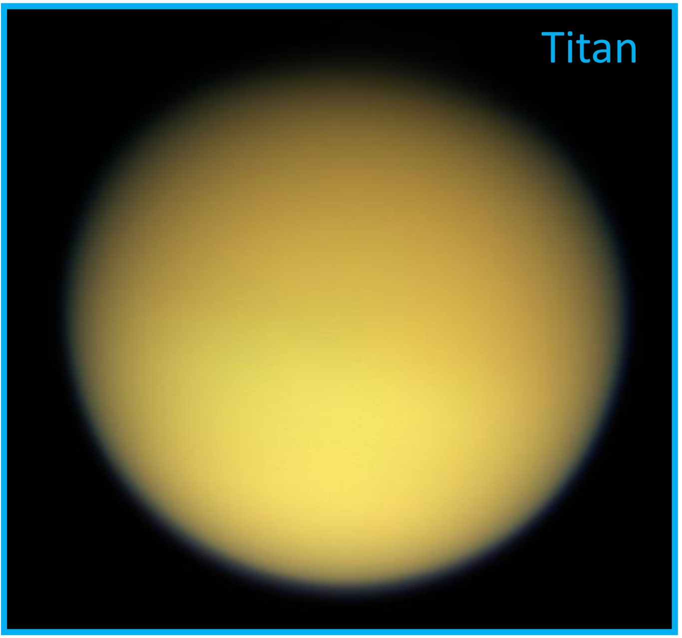
In nature

In astrophysics

- Planetary atmospheres (CH_4)
- Interstellar clouds (dark nebulae)

In the atmosphere

- Noctilucent clouds
- Polar Mesospheric Summer Echoes (PMSE)



for ex. Szopa et al. Planet. Space Sci. (2006)

for ex. Kovacevic et al. ApJ (2005)

for ex. Scales et al. New J. Phys. (2004)

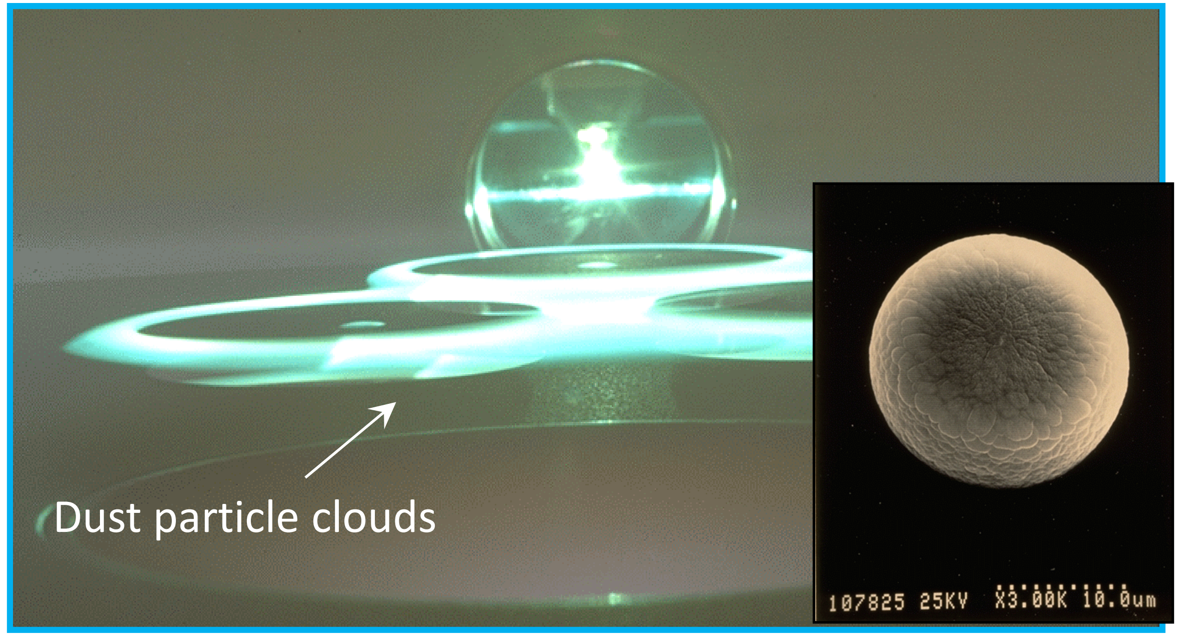
DUSTY (OR COMPLEX) PLASMAS?

In industry

Dust particles harmful
(End of 80s – beginning of 90s)

Surface processing in microelectronics (cleanliness is a major requirement)

- Thin film deposition
- Etching



G. Selwyn et al. J. Vac. Sci. Technol. A (1989)
R.M. Roth et al. Appl. Phys. Lett. (1985)

Use of reactive gases
Sputtering
→ **Dust particle formation**

DUSTY (OR COMPLEX) PLASMAS?

In industry

Dust particles useful
(End of 90s)

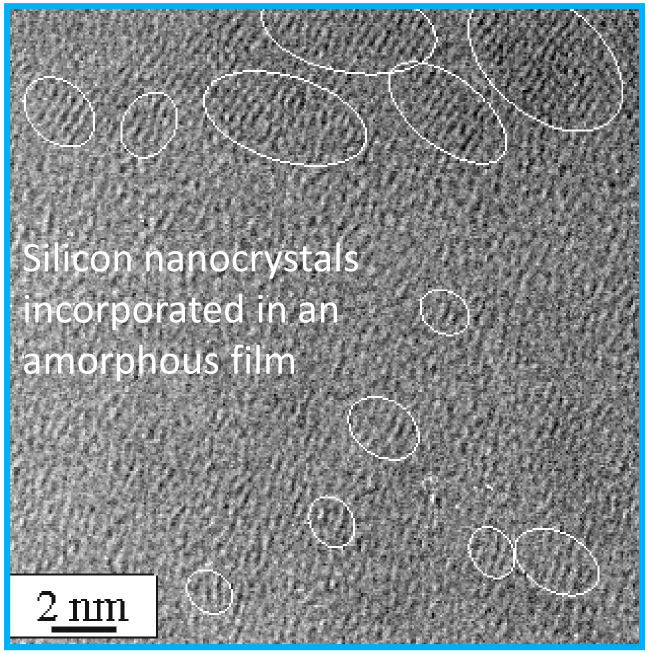
Dust particle formation (silicon, carbon)

Design of new materials
Nanotechnologies

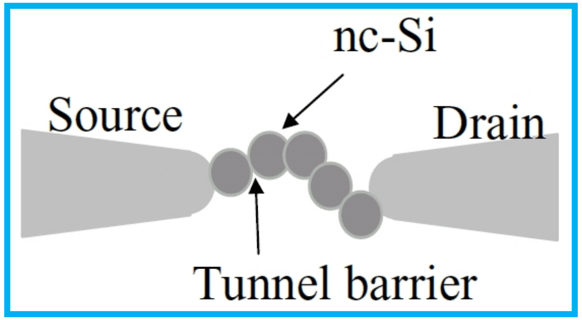
- Nanostructured materials
- Solar cells (polymorphous silicon)
  P. Roca i Cabarrocas J. Vac. Sci. Technol. A (1996)
- Single electron devices (transistor, memories)

CHALLENGE

Control the formation and deposition of grown nanoparticles (size, structure, number, position)



G. Viera et al. J. Appl. Phys. (2002)



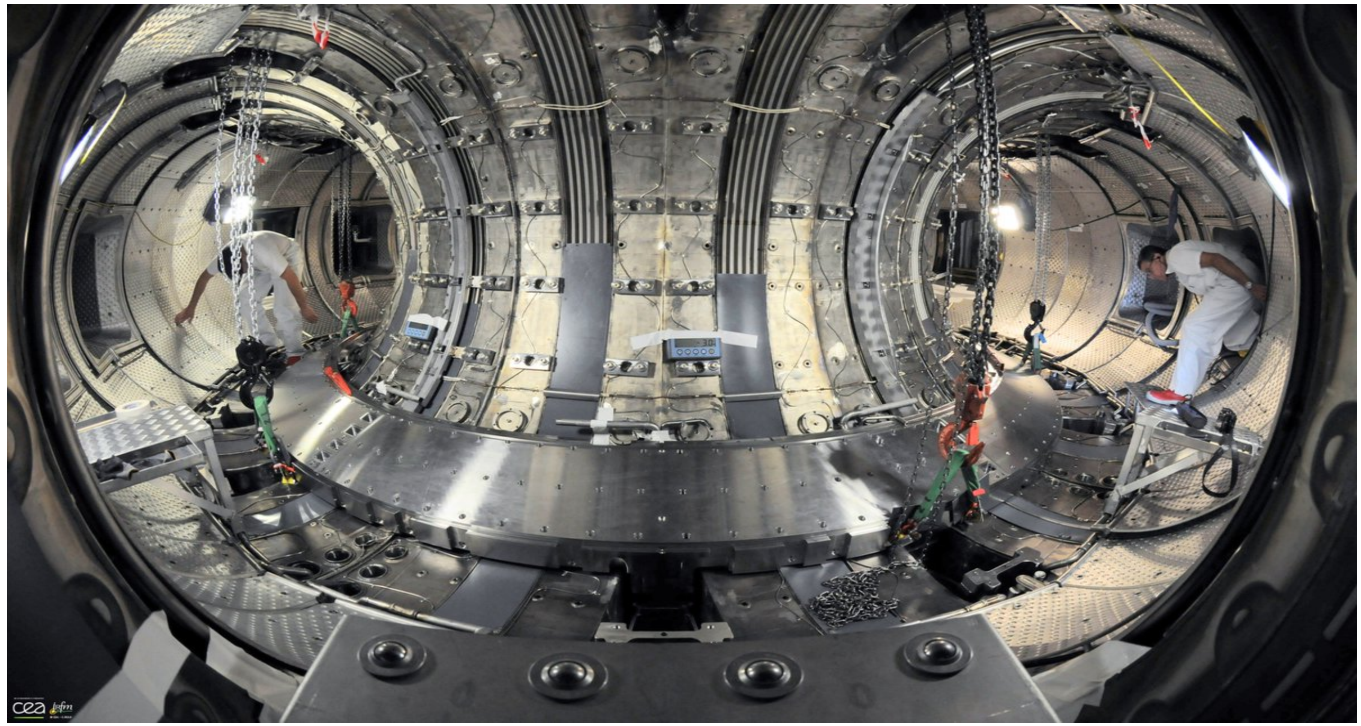
Transistor using silicon nanocrystals
A. Dutta et al. Jpn. J. Appl. Phys. (2000)

DUSTY (OR COMPLEX) PLASMAS?

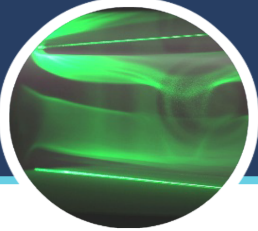
In fusion devices

Dust particles harmful

Wall erosion
Impurities in the plasma
Radio-toxicity of dust particles



J. Winter, Plasma Phys. Control. Fusion (2004)
C. Arnas et al. J. Nucl. Mater (2009)
S.I. Krasheninnikov et al. Plasma Phys. Control. Fusion (2008)
D.L. Rudakov et al. Rev. Sci. Instrum. (2008)



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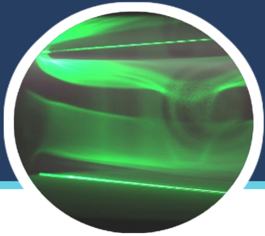
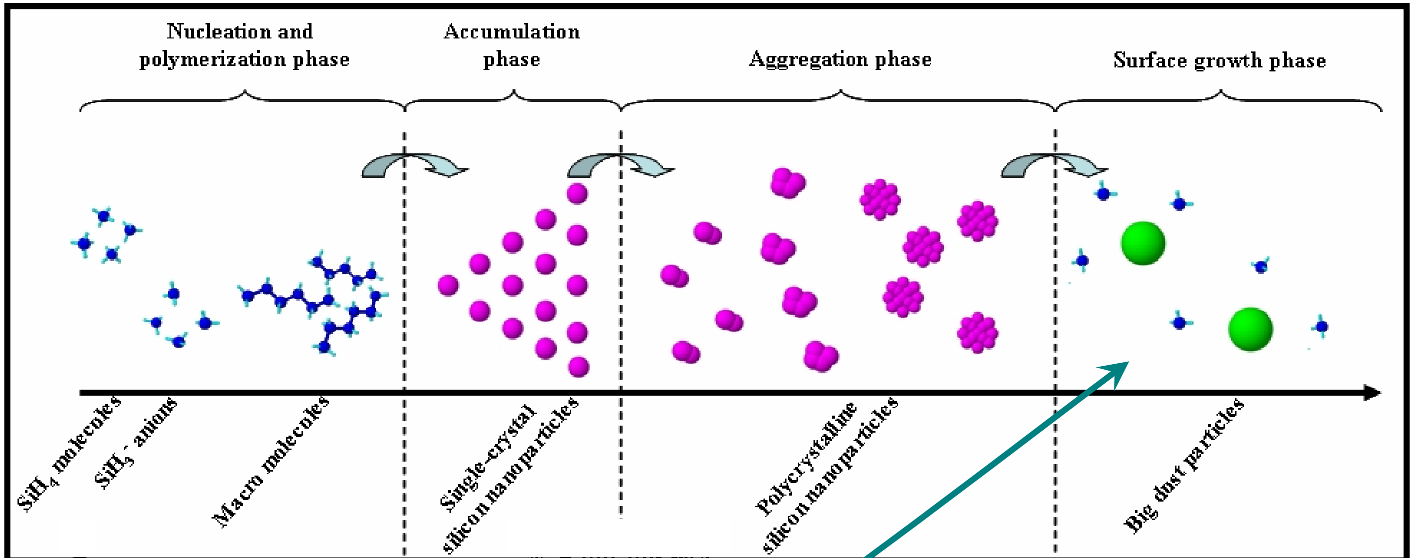


NANOPARTICLE FORMATION

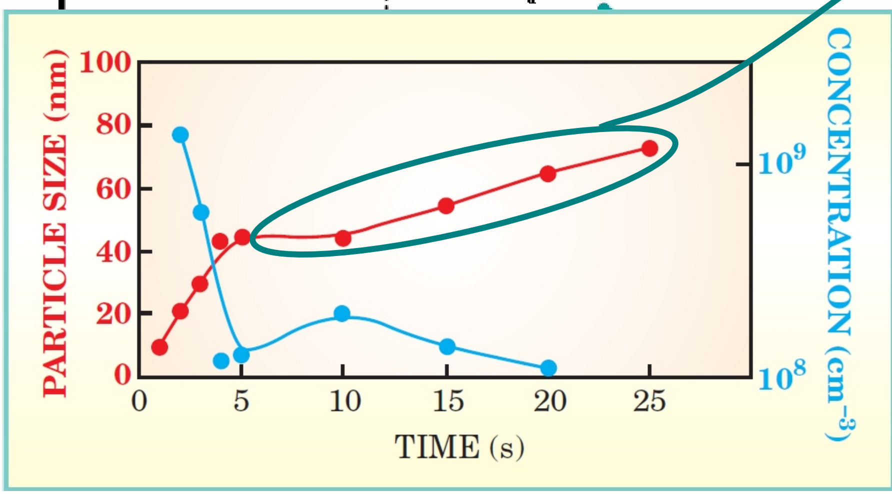


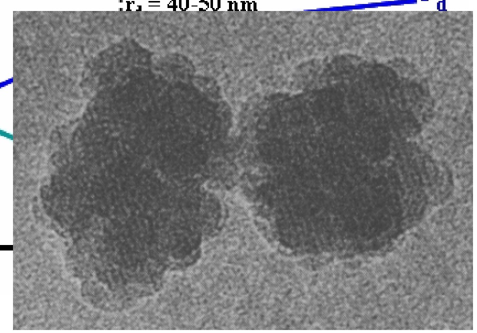
Cavarroc PhD Thesis (2007)

see also Bouchoule *et al.* Pure Appl. Chem. (1996)

Aggregation is still an open debate due to the dust particle charge

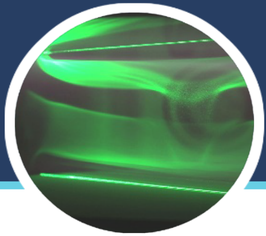
Ravi *et al.* Phys. Rev. E (2009)
Michau *et al.* J. Appl. Phys. (2017)





Nanoparticle electrical charge is a crucial parameter for the whole dusty plasma system

Bouchoule *et al.* Plasma Sources Sci. Technol. (1993)
from Merlino *et al.* Phys. Today (2004)



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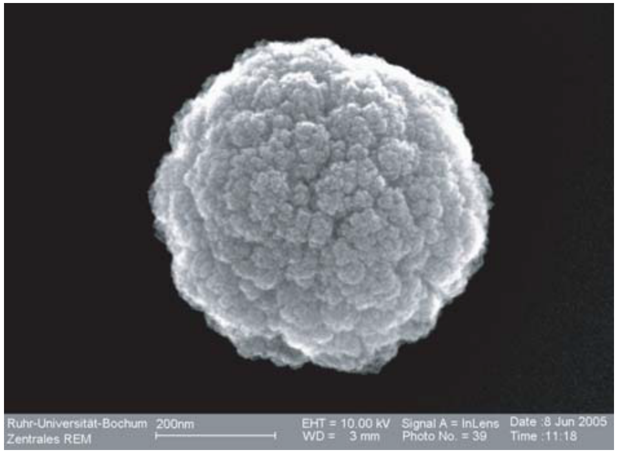
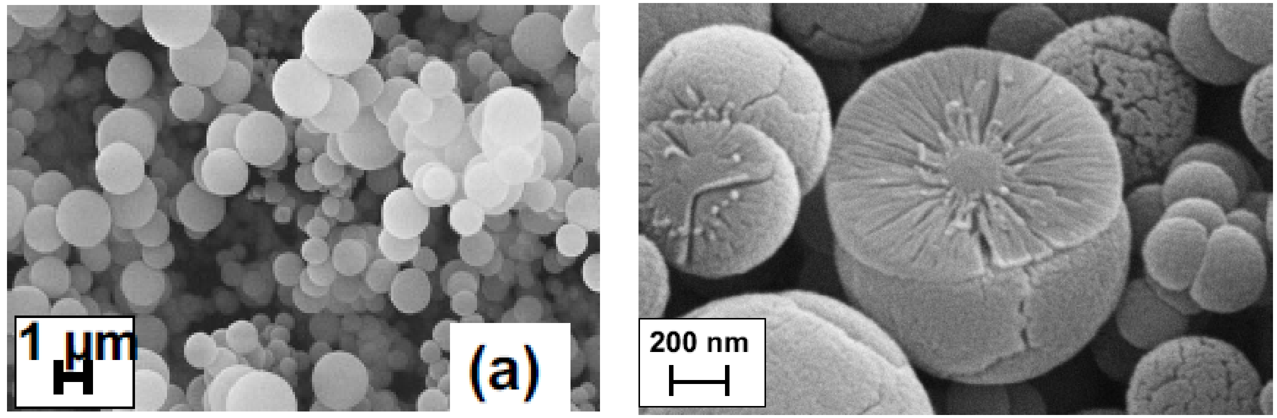


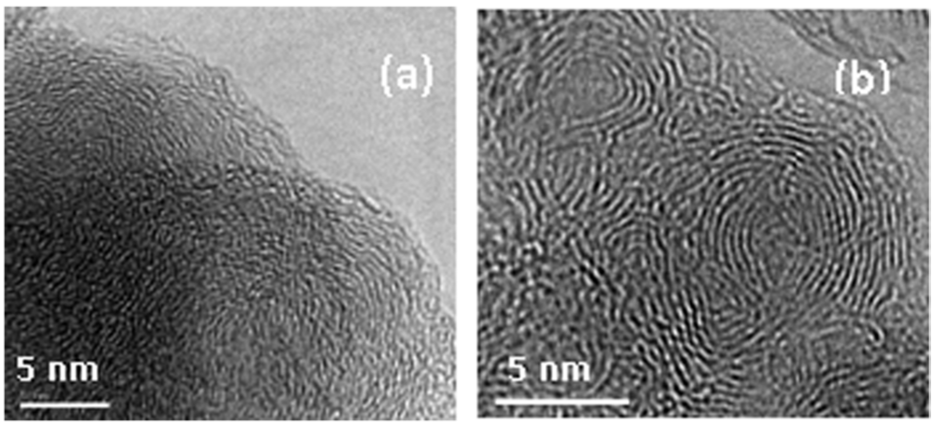
Ar/C_2H_2 (r_d=180 nm)

Berndt et al. Contrib. Plasma Phys. (2009)



CH_4/N_2

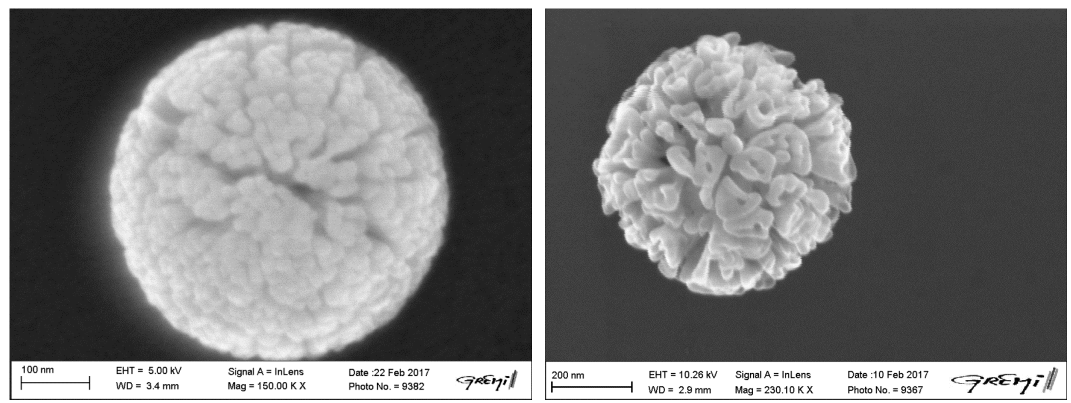
Massereau-Guilbaud et al. J. Appl. Phys. (2009)



Graphite DC sputtering

Ar/CH_4/H_2 µwave

C. Arnas et al. Plasma Phys. Control. Fusion (2010)

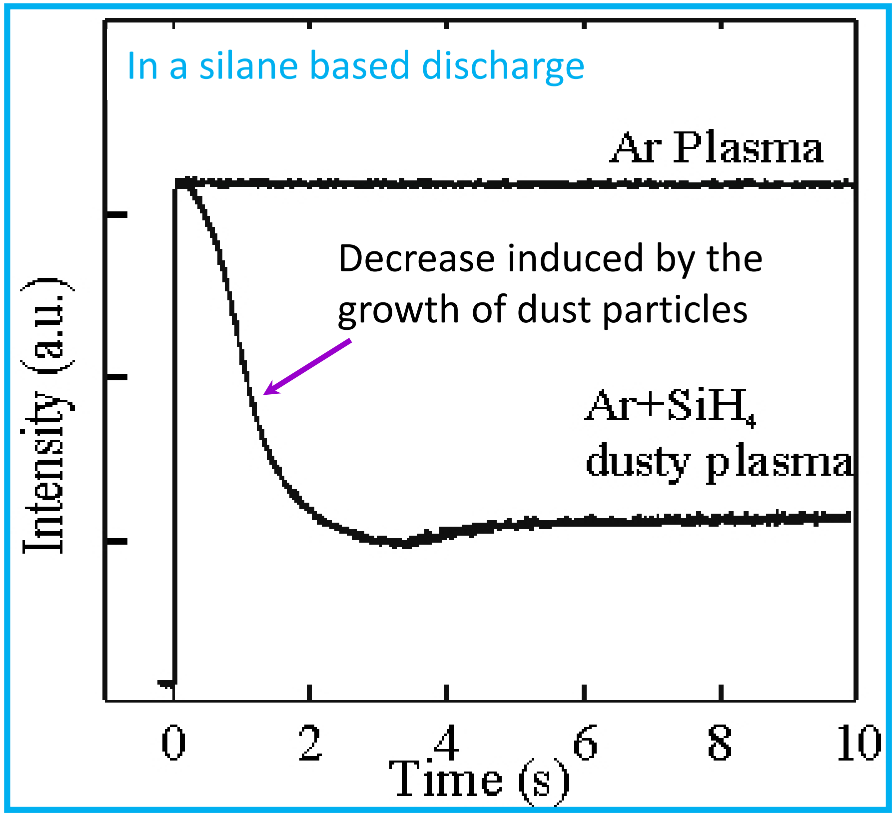


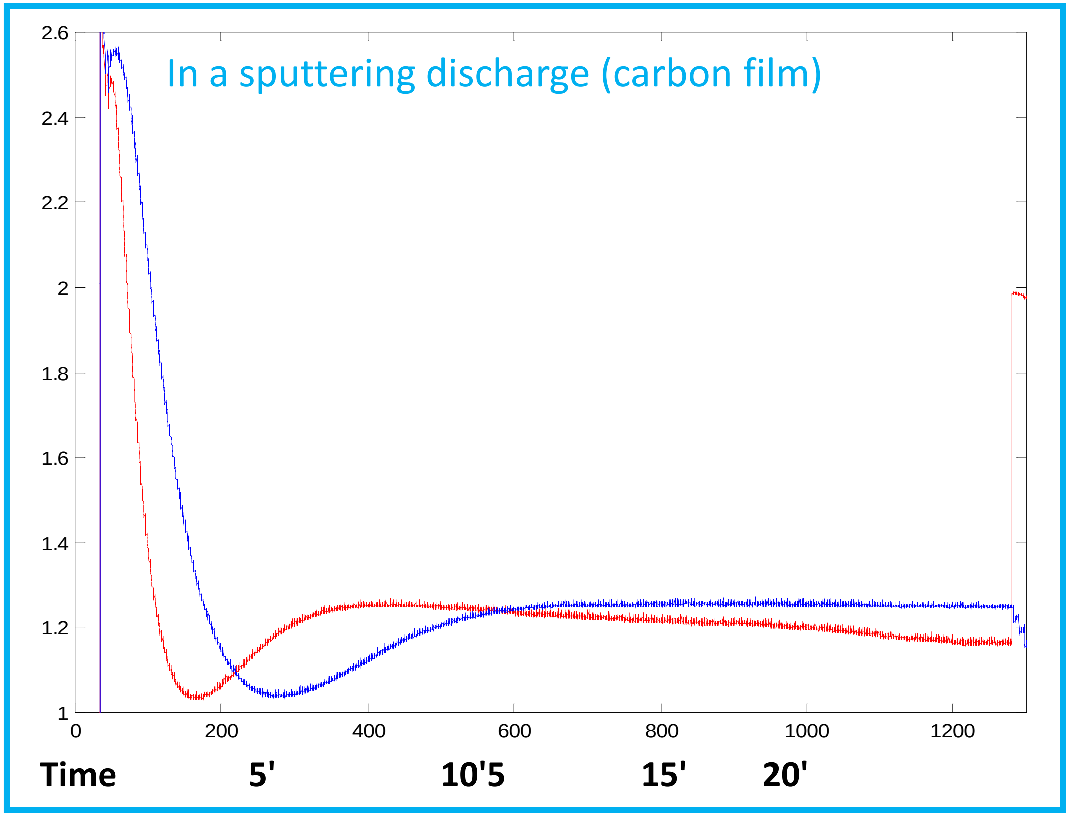
Carbon based film sputtering (Ar/C_2H_5OH)

Labidi et al. AIP Conf. Proc. (2018)

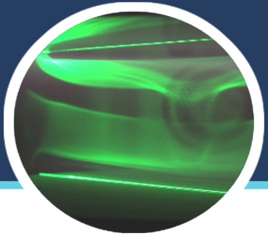
Charging process of nanoparticles is "universal", whatever the chemistry

All types of electrical measurements are able to detect nanoparticles
Example of the discharge current (see also Boufendi *et al.* Appl. Phys. Lett. (2001))

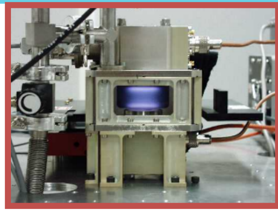




M. Mikikian *et al.* New J. Phys. **5**, 19 (2003)



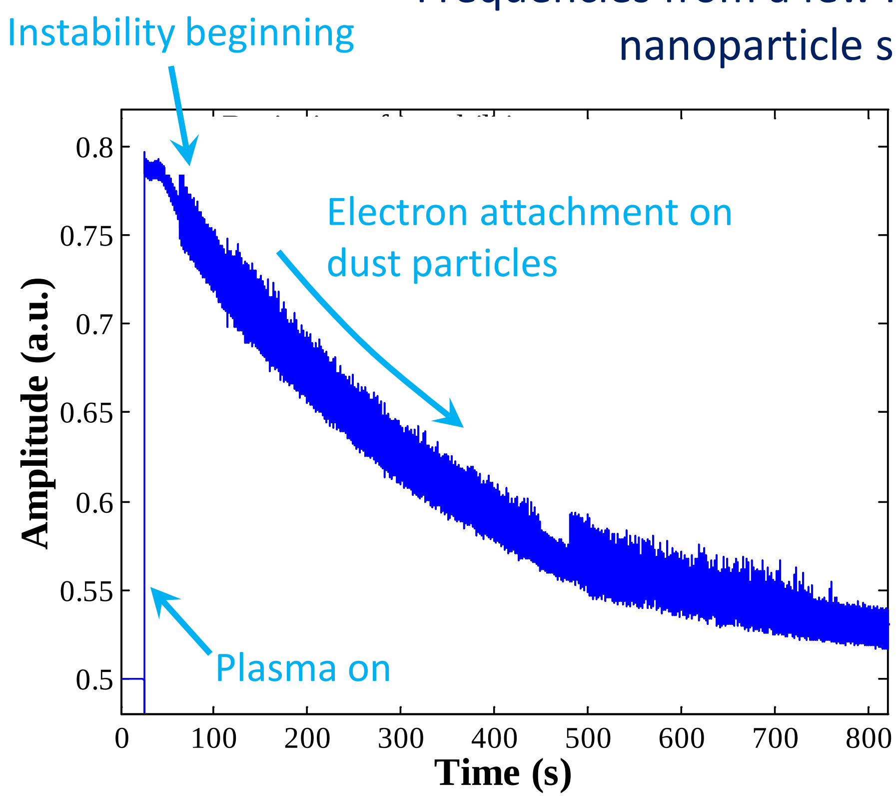
NANOPARTICLE FORMATION



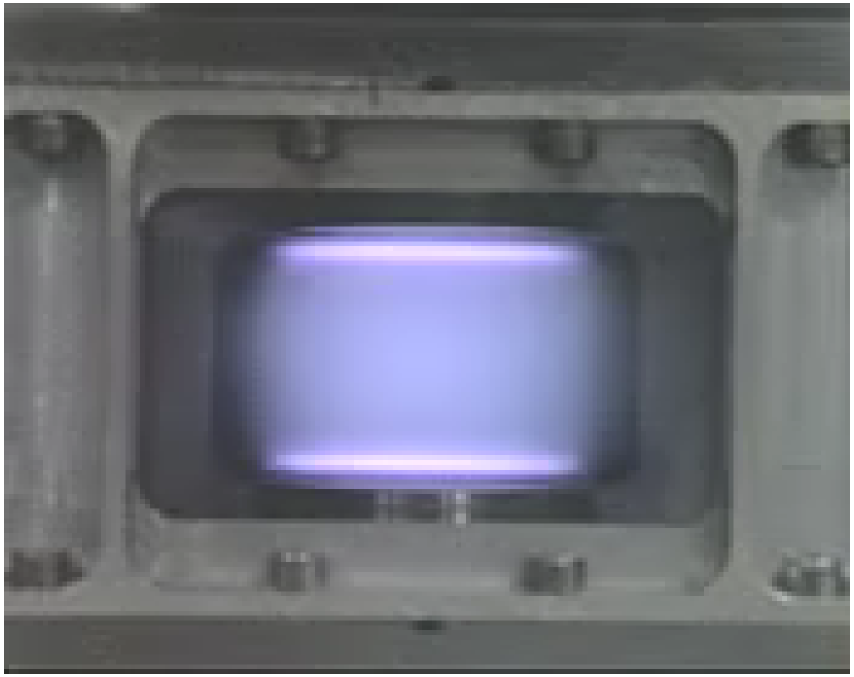
When nanoparticle density is large, huge loss of electrons

Plasma equilibrium is disturbed → Low frequency Instabilities

Frequencies from a few Hz to a few kHz depending on the nanoparticle size, density and charge



Mikikian *et al.* Phys. Plasmas **13**, 092103 (2006)
Tawidian *et al.* Plasma Sources Sci. Technol. **23**, 065009 (2014)



Mikikian *et al.* Eur. Phys. J Appl. Phys. **49**, 13106 (2010)
Mikikian *et al.* IEEE Trans. Plasma Sci. **36**, 1012 (2008)

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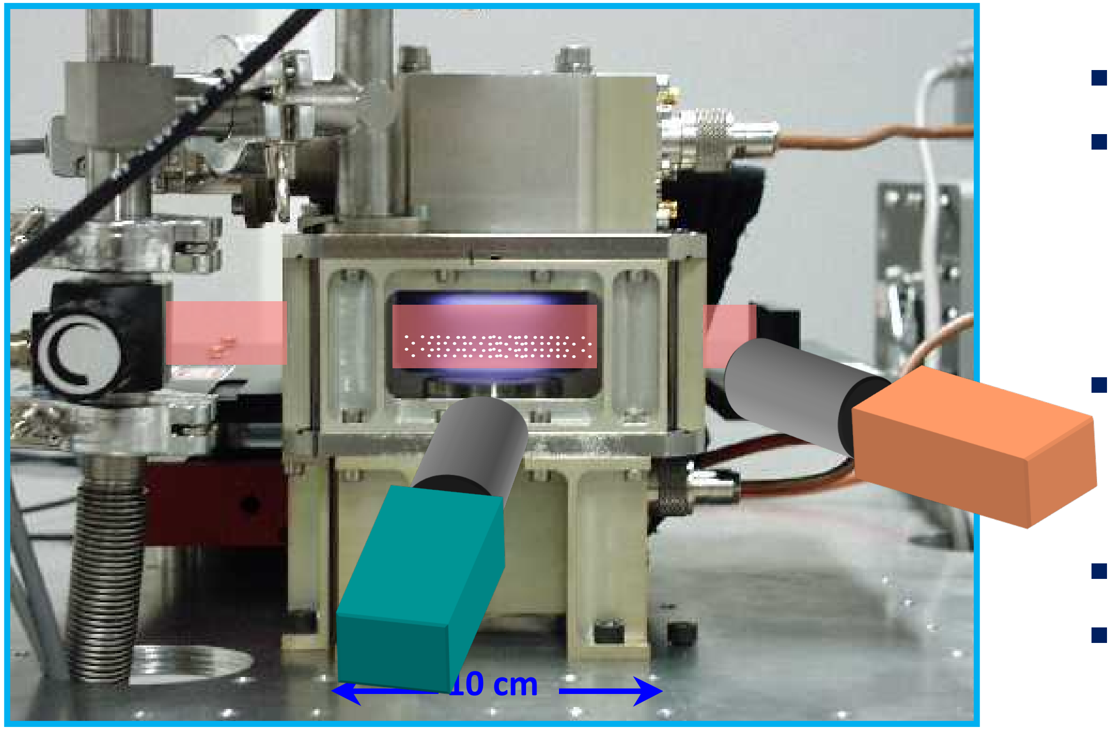
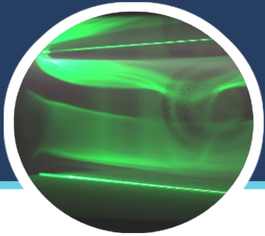
EXPERIMENTAL SETUP

RF discharge (13.56 MHz) in push-pull mode
Electrode diameter = 4 cm, Inter-electrode distance = 3 cm
Ar or Kr plasma at pressure 0.1 $\rightarrow$ 2 mbar (no gas flow), power 0 $\rightarrow$ 4 Watts

Nanoparticle formation by sputtering a polymer layer (final diameter ~ 50$\rightarrow$800 nm)



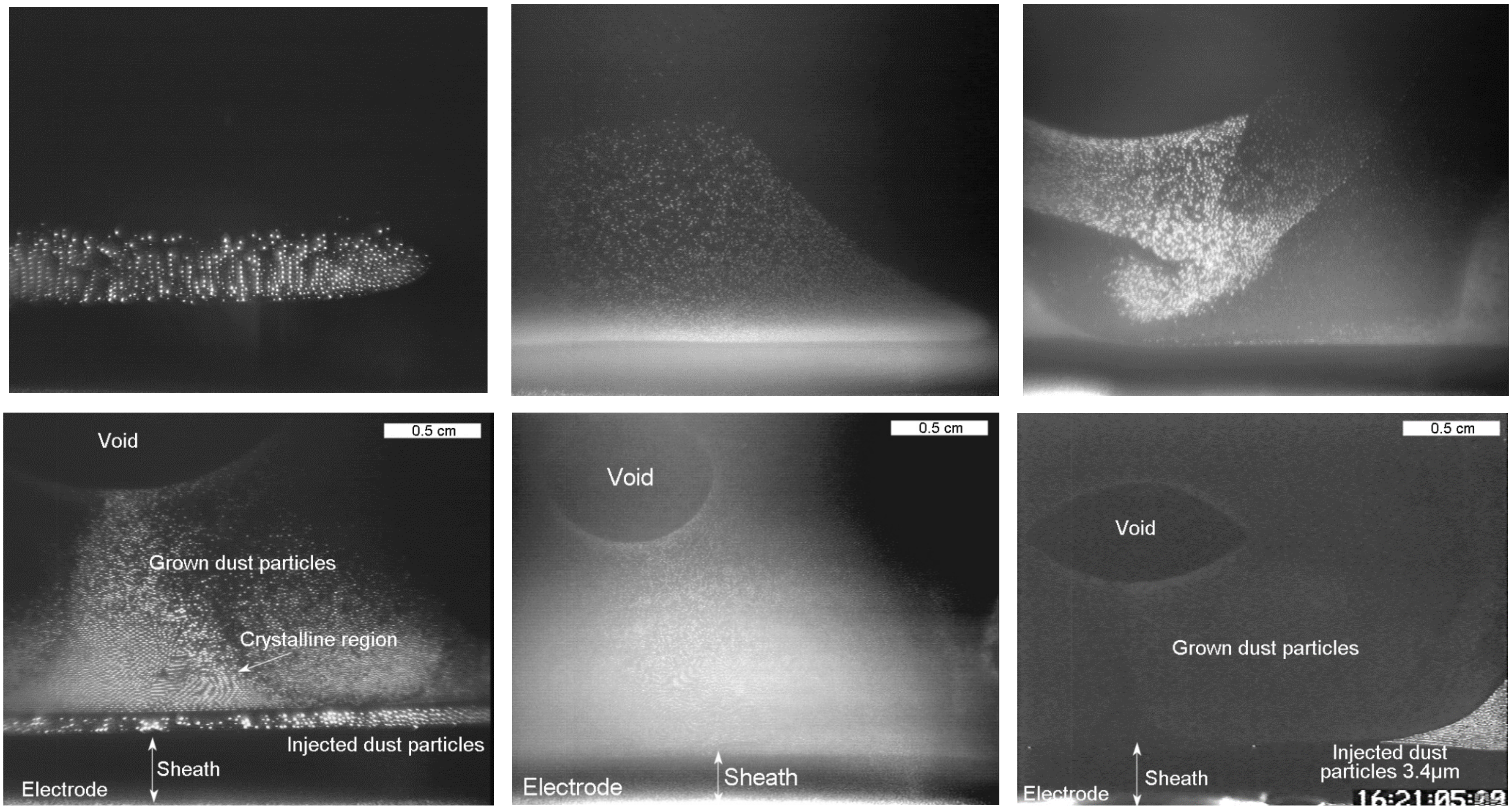
- Electrical probe (V, I)
- Optical Emission Spectrometer
  - F=500 mm
  - Gratings 600, 1200, 1800, 2400 lines/mm
  - CCD detector 400x1340 pixels
- Laser Light Scattering
  - Laser sheet
  - Normal and high-speed imaging
- Laser Induced Fluorescence
- Absorption Spectroscopy



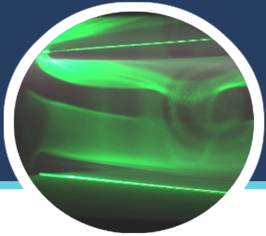
EXPERIMENTAL SETUP

Forces : shape of the dust cloud

Gravity, Electric force, Ion drag, Neutral drag, Thermophoresis, Interactions



M. Mikikian, Habilitation (2008)



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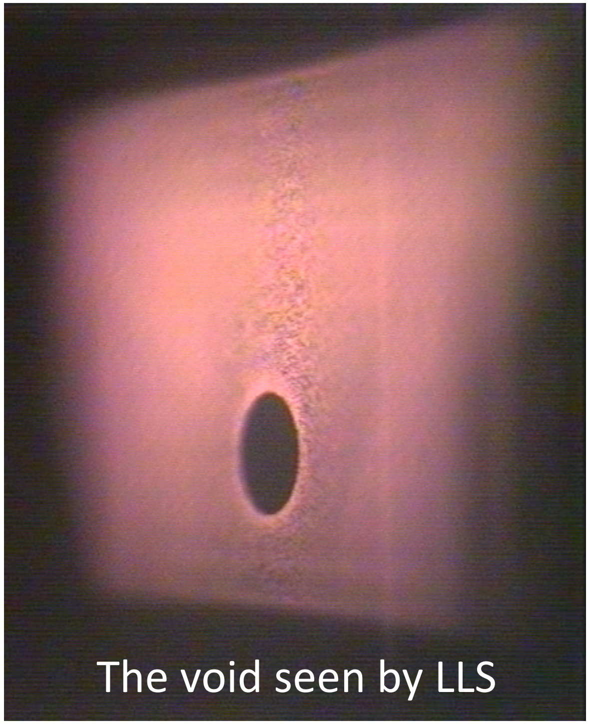
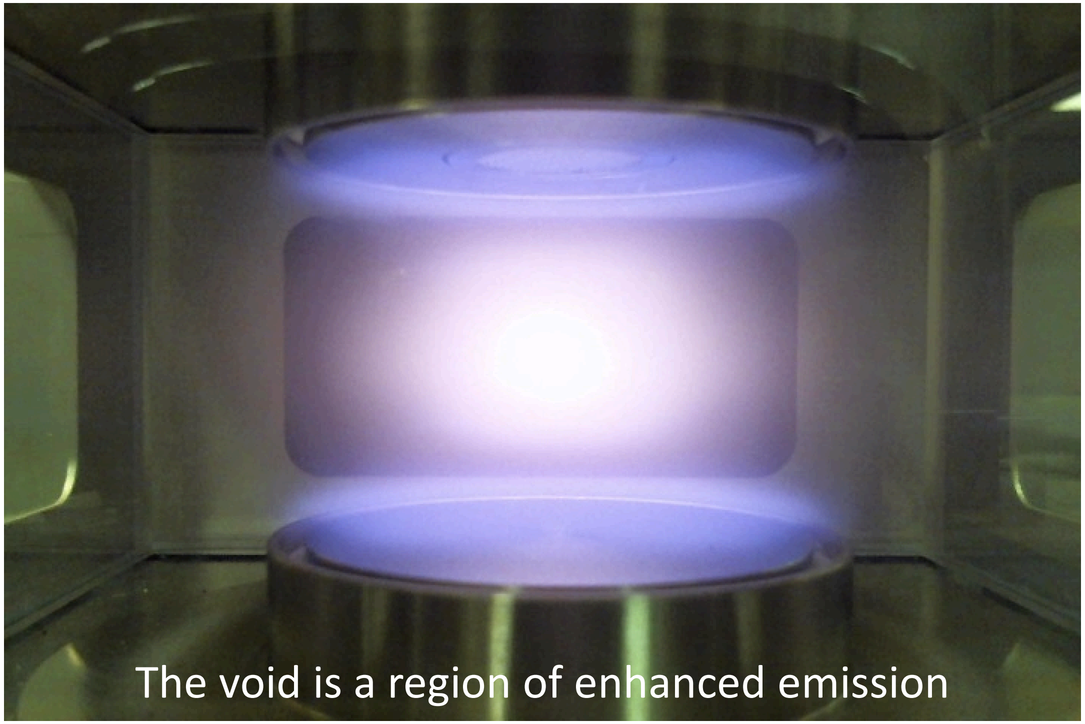
THE VOID: A DUST-FREE REGION

In typical cc-rf discharges a dust-free space appears close to the plasma center

This void is induced by the ion drag force and appears when dust particles reach a sufficiently large size (charge)



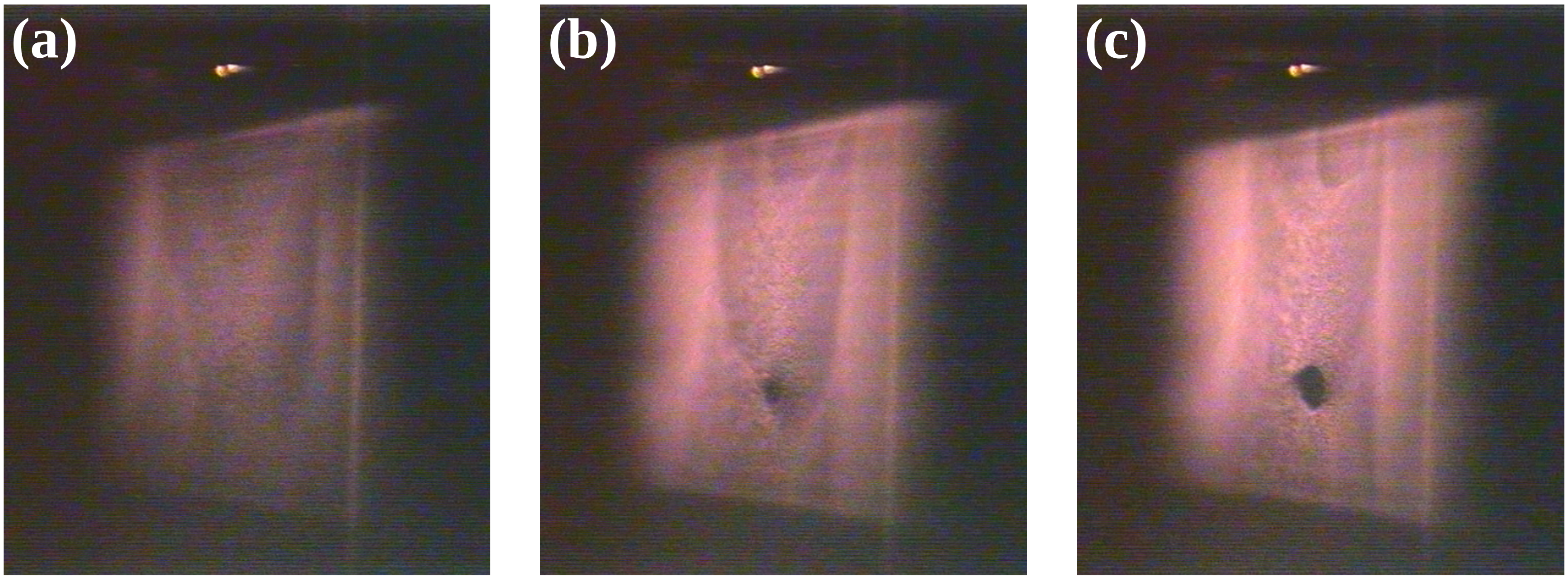


Mikikian *et al.* Eur. Phys. J. Appl. Phys. **49**, 13106 (2010)

THE VOID: A DUST-FREE REGION

In typical cc-rf discharges a dust-free space appears in the cloud when dust particles reach a sufficiently large size (charge)

This void is induced by the ion drag force (J. Goree et al. Phys. Rev. E (1999))



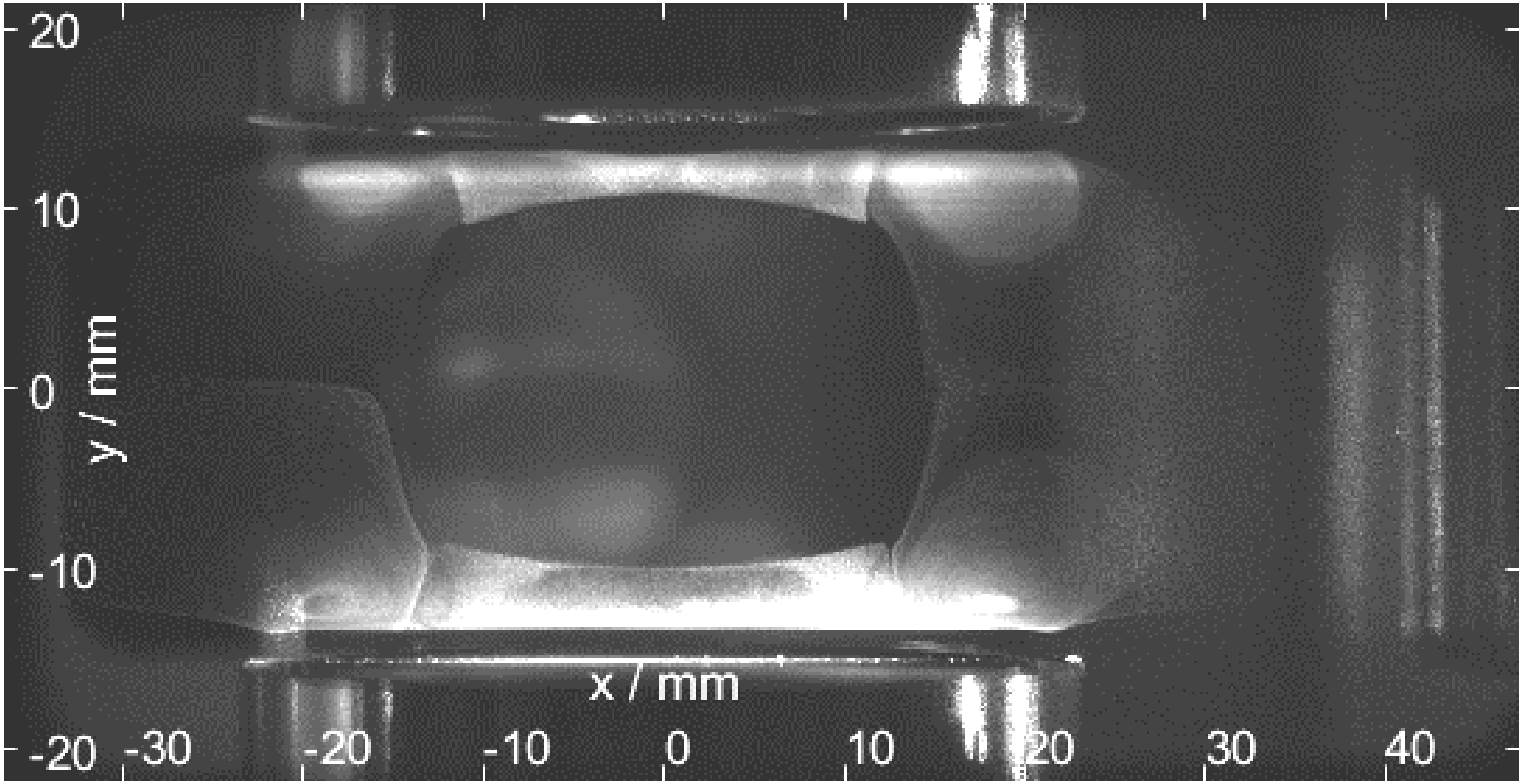
M. Mikikian et al. Pure Appl. Chem. (2010)

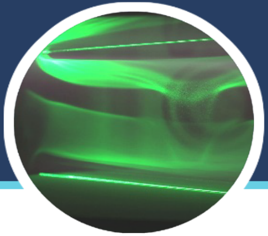
See also

- J. Dorier et al. J. Vac. Sci. Technol. (1995)
- G. Praburam et al. Phys. Plasmas (1996)
- G.E. Morfill et al. Phys. Rev. Lett. (1999)
- M.R. Akdim et al. Phys. Rev. E (2001)
- S.V. Vladimirov et al. Phys. Plasmas (2005)
- V. Land et al. New J. Phys. (2007)

THE VOID: A DUST-FREE REGION

In the void, conditions are fulfilled for the nucleation of new nanoparticle generations





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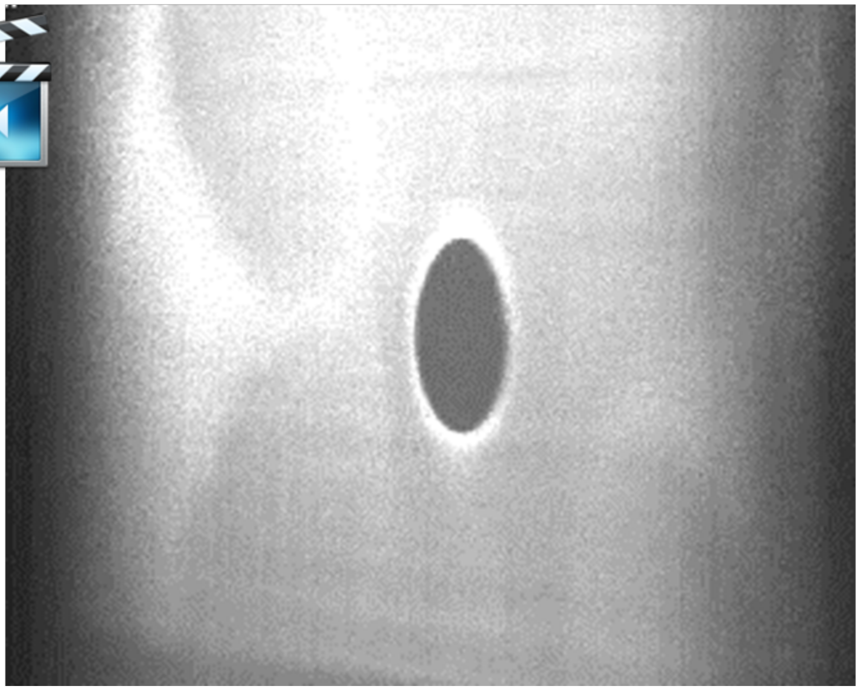
VOID INSTABILITIES: HEARTBEAT

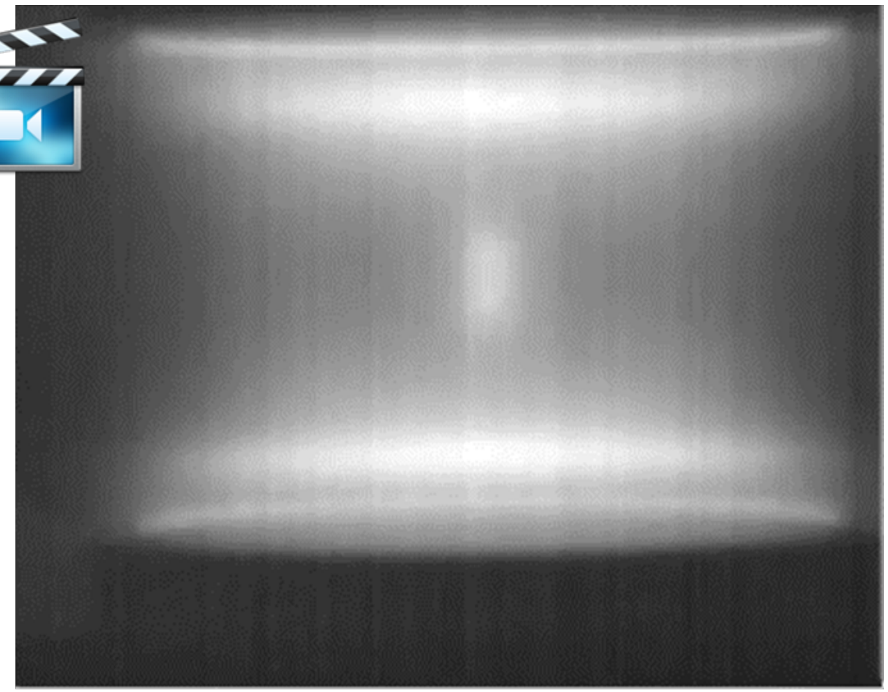
Void sustained by 2 forces of opposite directions (ion drag/electric force)

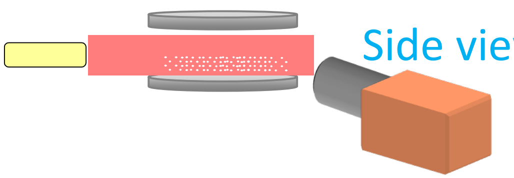
Heartbeat instability = Self-excited oscillations of the void size (~ 20 Hz)

Dust cloud observed with Laser Light Scattering



Direct observation of plasma glow

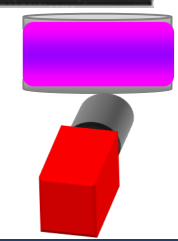




Side view

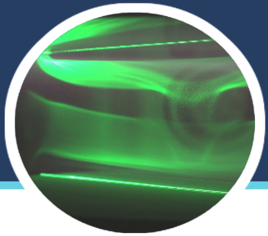
High-speed imaging ~1800 fps

Front view



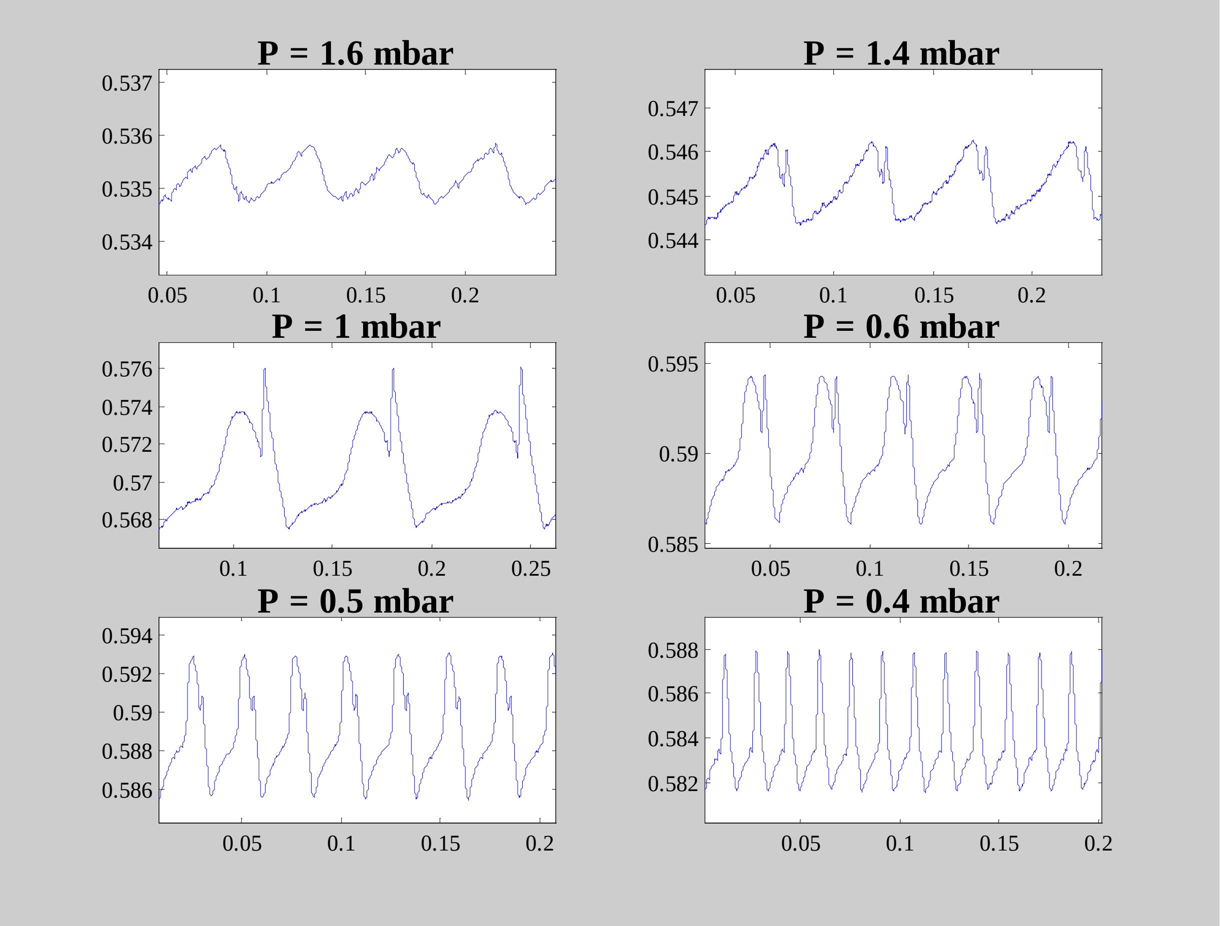
M. Mikikian et al. New J. Phys. (2007)

M. Mikikian et al. Phys. Rev. Lett. (2010)

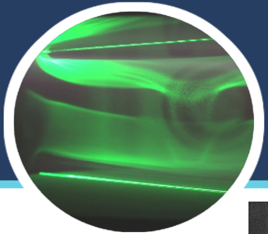


VOID INSTABILITIES: HEARTBEAT

Signature on electrical measurements (discharge current)
Strongly nonlinear behavior



M. Mikikian et al. Phys. Plasmas (2004)



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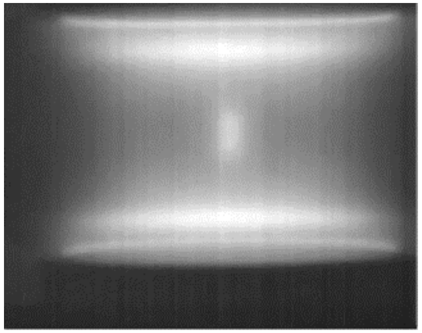
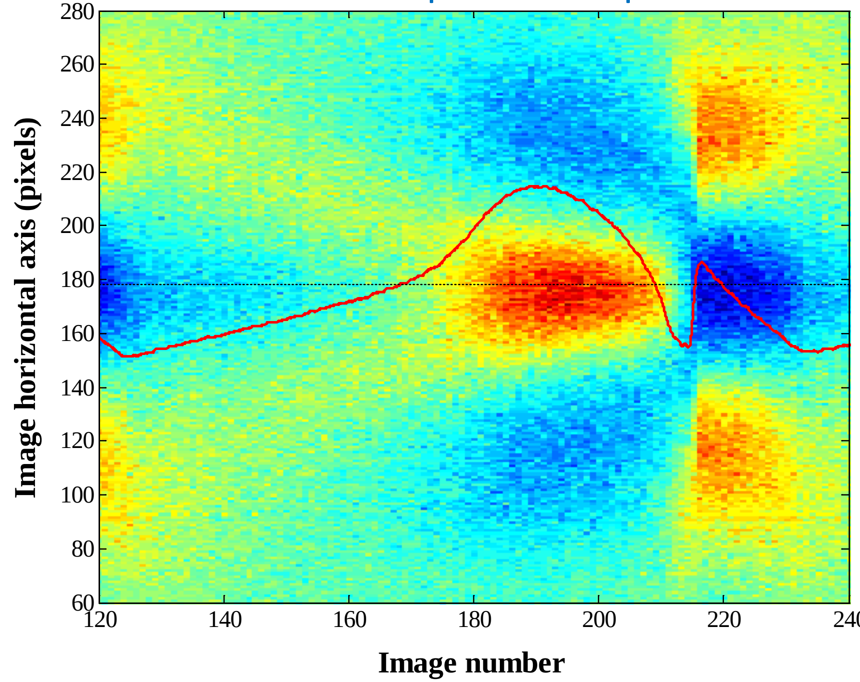
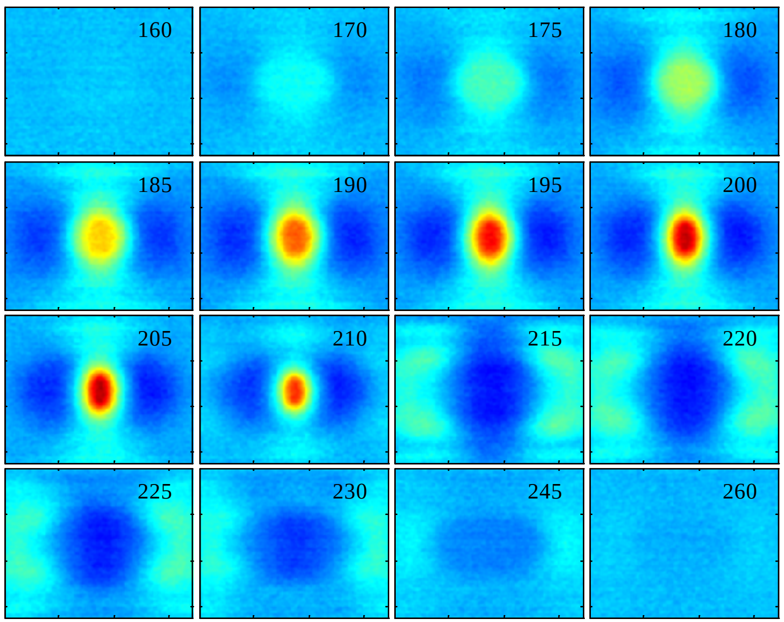


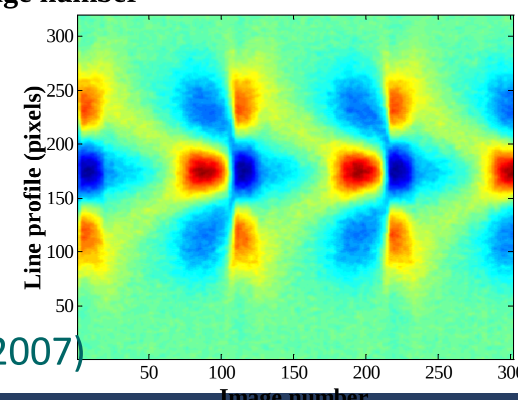
Direct observation of the plasma glow

Evolution of the central line profile during a single contraction-expansion sequence



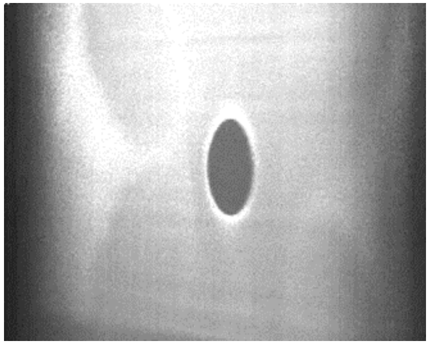
Evolution of plasma glow during a single contraction-expansion sequence





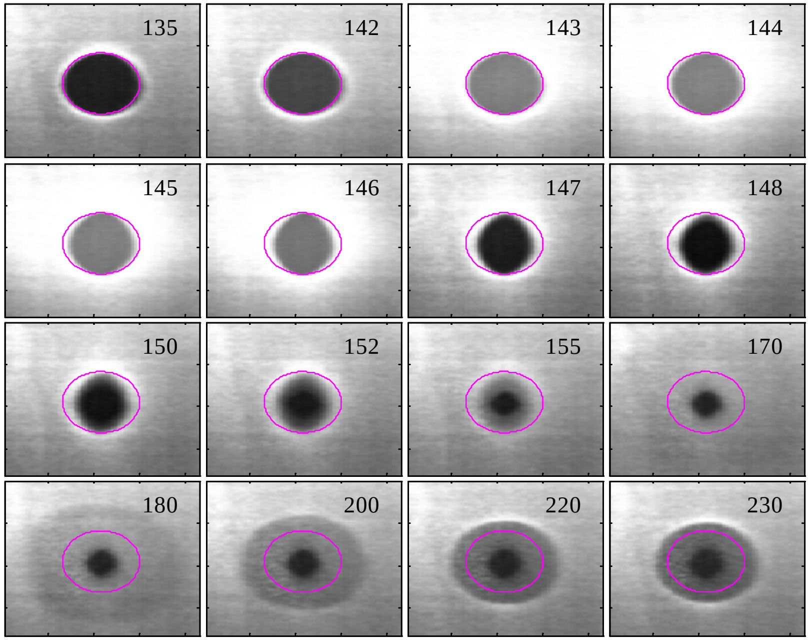
M. Mikikian, L. Couëdel, M. Cavarroc, Y. Tessier, L. Boufendi, New J. Phys. **9**, 268 (2007)

VOID INSTABILITIES: HEARTBEAT

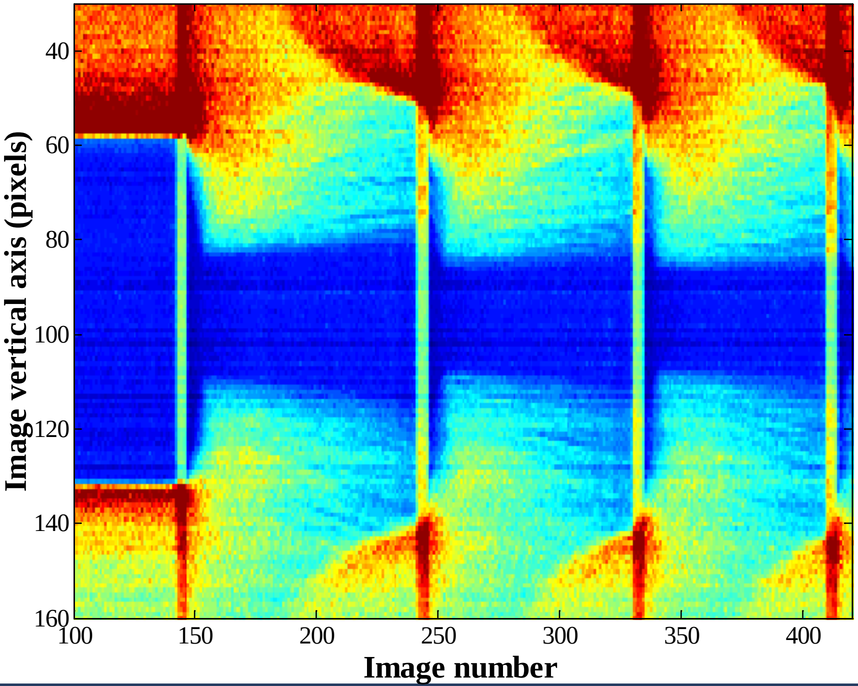


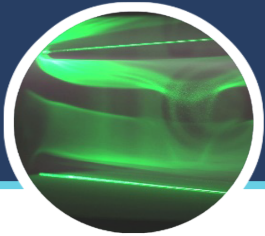
Dust cloud observed with Laser Light Scattering

Evolution of dust cloud during one contraction-expansion sequence



Evolution of the central column profil during one contraction-expansion sequence





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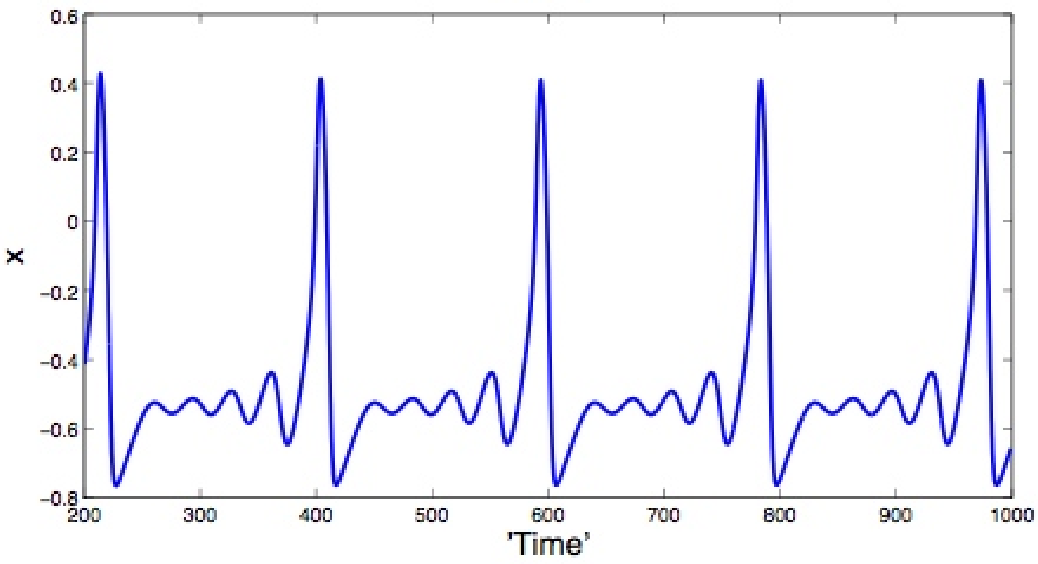
- ❑ Experimental setup
- ❑ The "void"
- ❑ Void instabilities: Heartbeat
- ❑ **Last beats: Mixed-Mode Oscillations**

MIXED-MODE OSCILLATIONS

MMOs = Alternation of small and large amplitude oscillations

Small amplitude oscillations = subthreshold oscillations
High amplitude oscillations = relaxation mechanisms (spikes)

$L^S = 1^4$



MMO notation:
A pattern with L large amplitude oscillations and S small amplitude ones is noted L^S

MIXED-MODE OSCILLATIONS

Chemistry: Belousov-Zhabotinskii (BZ) reaction (oxidation of malonic acid in sulfuric acid solution with bromate ions and a catalyst)

Electrochemical systems (copper-phosphoric acid)

Neuronal science: Models of neuronal activity

Hodgkin-Huxley

FitzHugh-Nagumo

Morris-Lecar

Dynamical system theories (bifurcation): Canards (French Ducks)

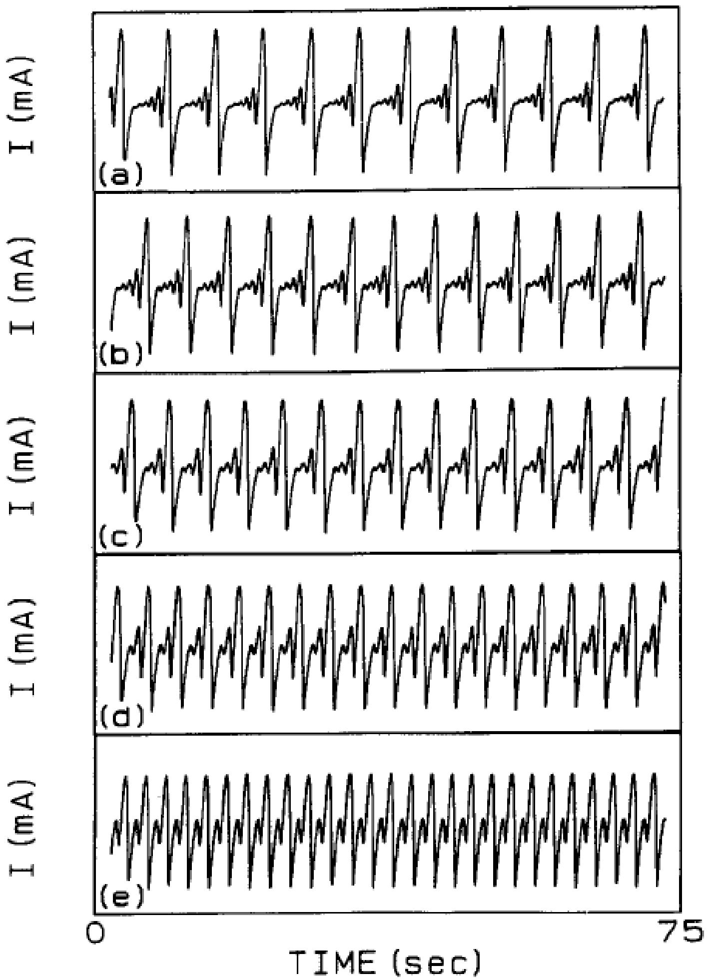
Subcritical Hopf-homoclinic bifurcation

Shilnikov homoclinic orbits

MIXED-MODE OSCILLATIONS

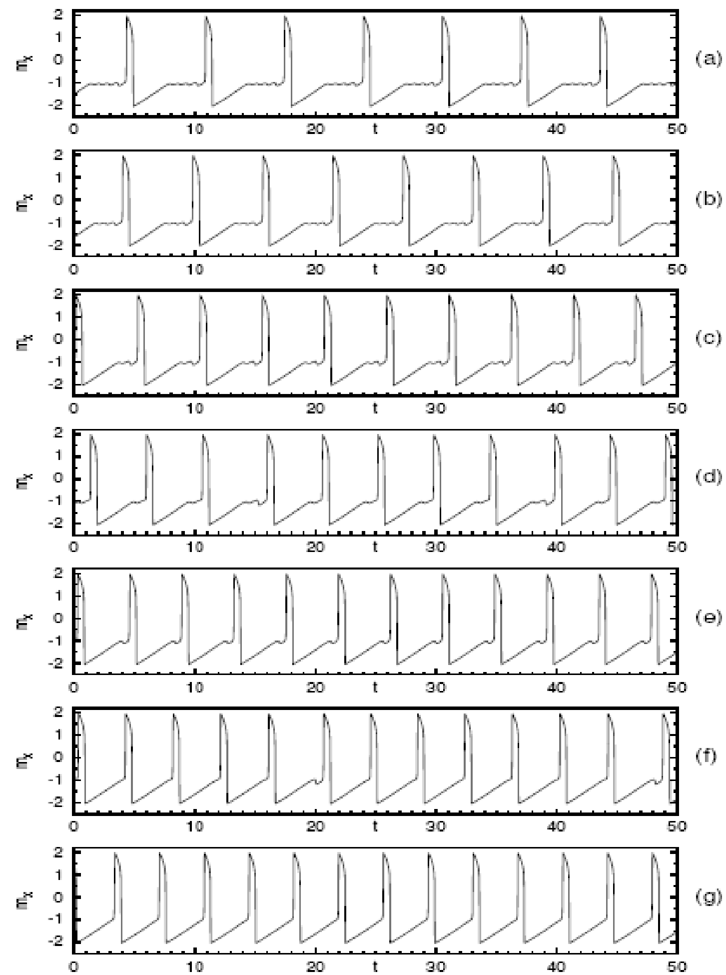
MMOs in electrochemical systems

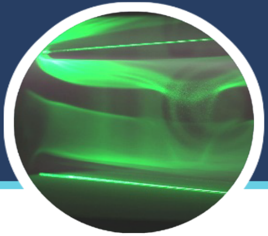
Schell et al., J. Chem. Phys. (1989)



MMOs in giant squid axon (FHN model)

Zaks et al., Chaos (2005)

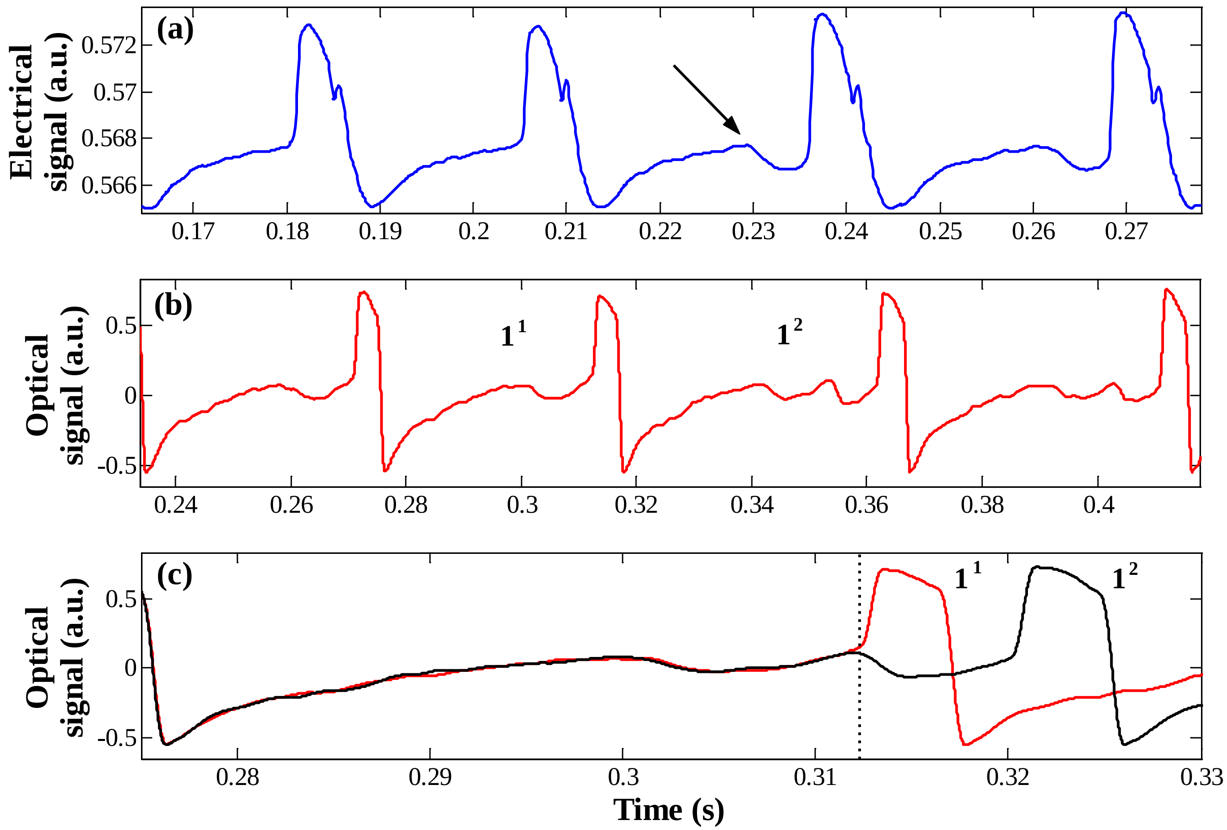




HEARTBEAT INSTABILITIES: LAST BEATS…

When the instability is about to stop, failed peaks occur

Signal shape is typical of MMOs



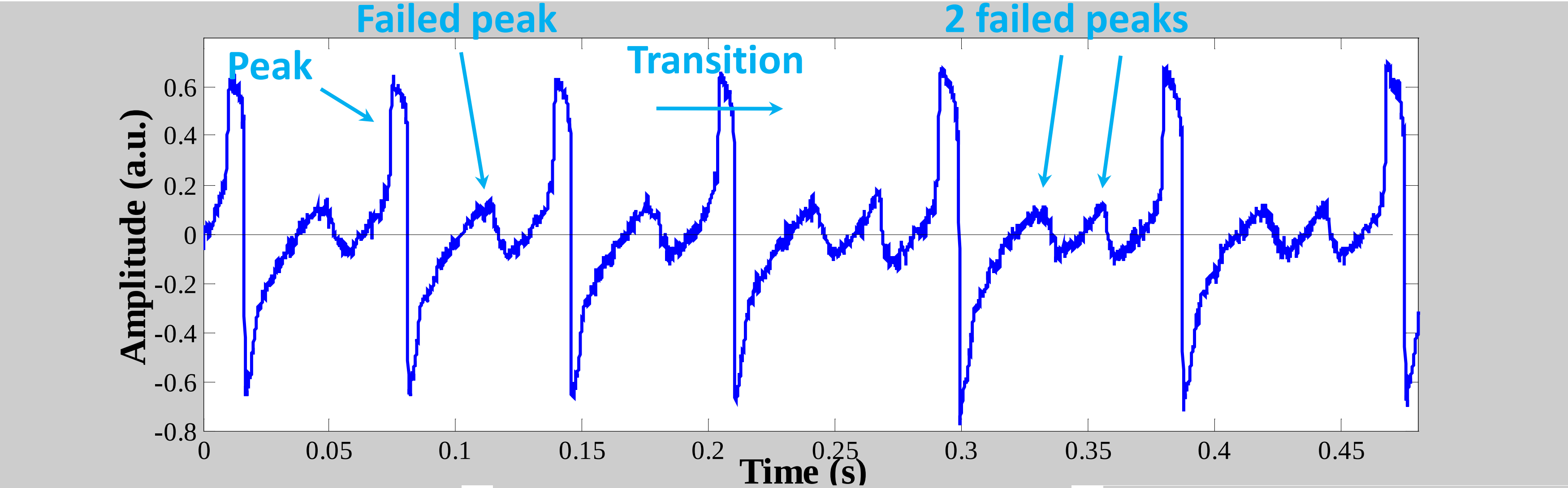
Transition between 1^0 and 1^1 states in discharge current

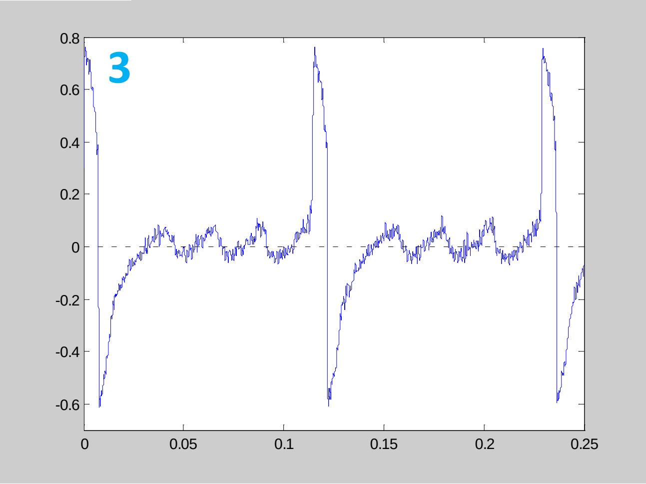
Transition between 1^1 and 1^2 states in plasma emission intensity

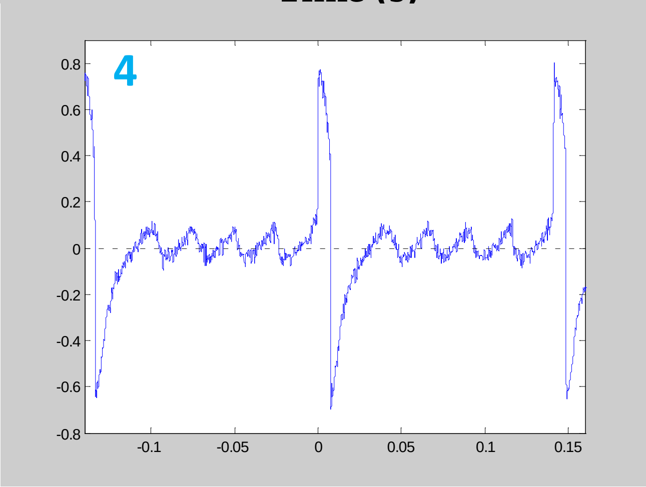
M. Mikikian, M. Cavarroc, L. Couëdel, Y. Tessier, L. Boufendi, Phys. Rev. Lett. **100**, 225005 (2008)

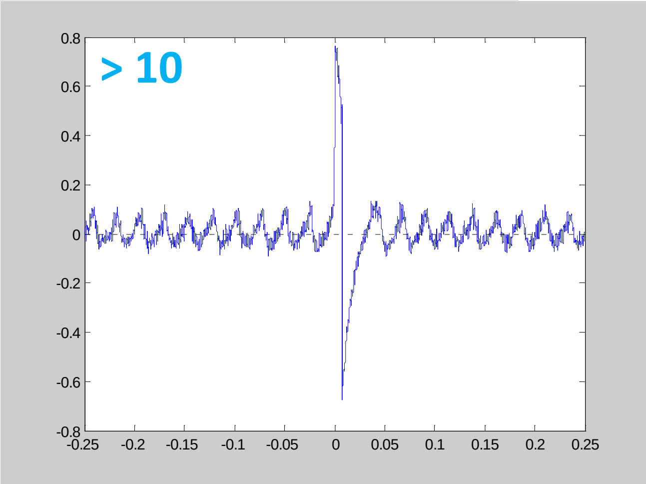
HEARTBEAT INSTABILITIES: LAST BEATS…

Signature on electrical measurements (discharge current)





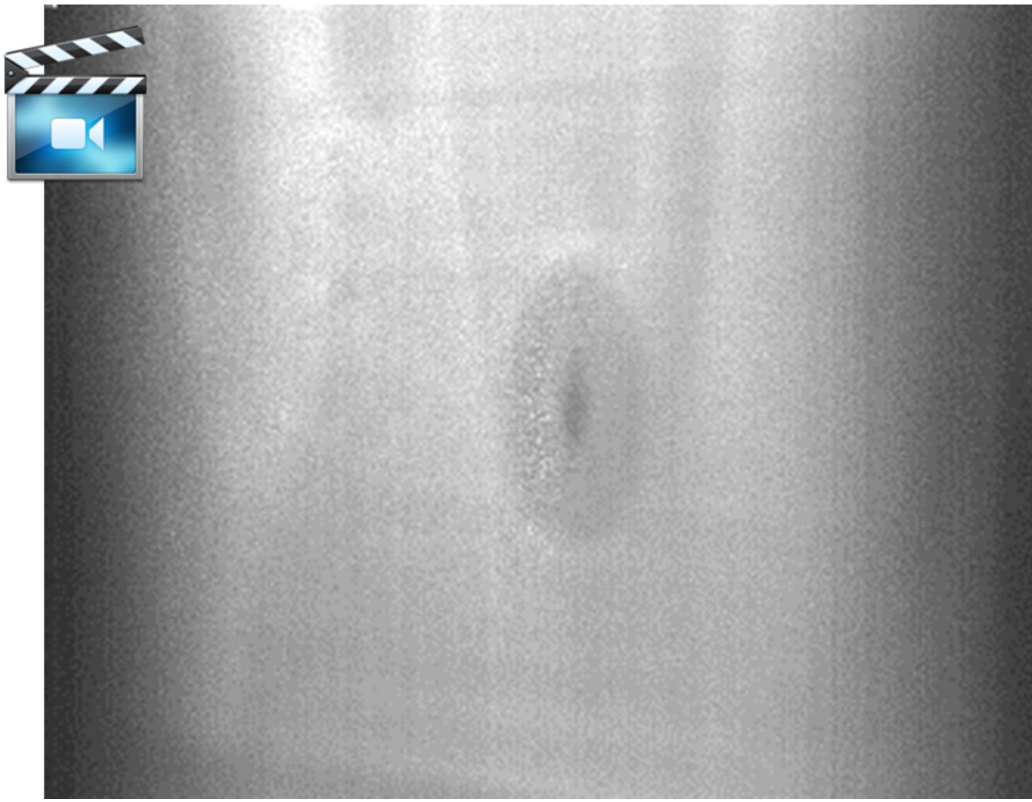




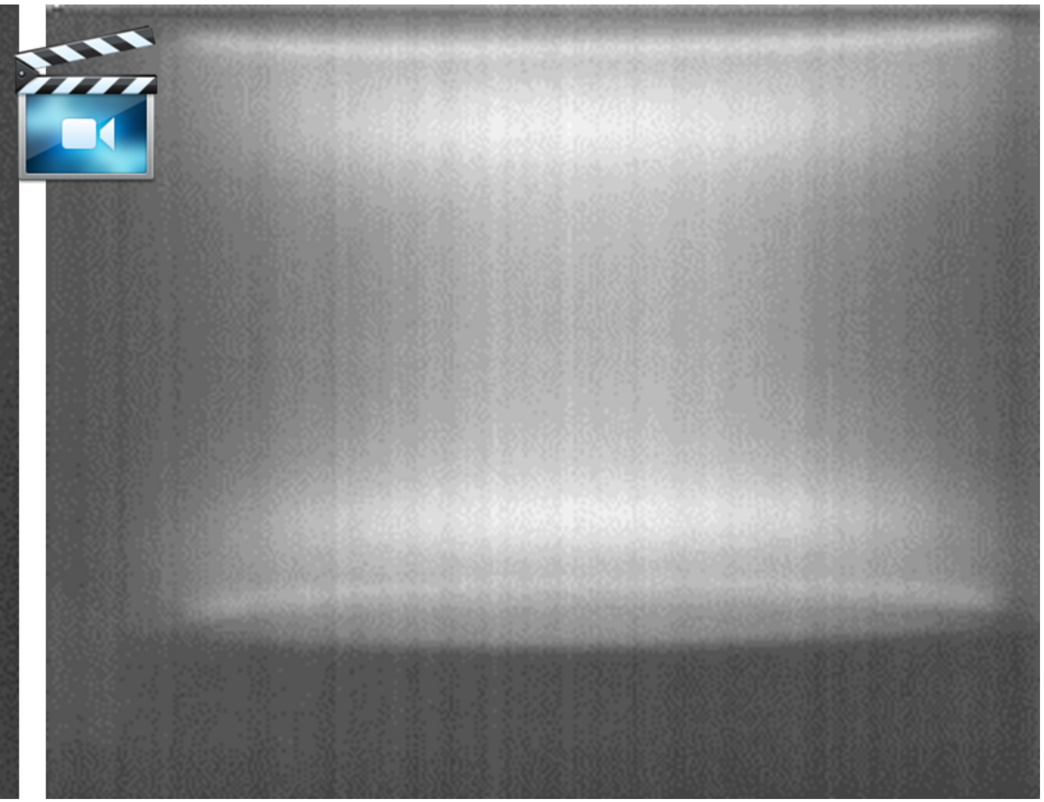
HEARTBEAT INSTABILITIES: LAST BEATS…

Contraction = Increase of central plasma emission
Failed peaks = Failed contractions

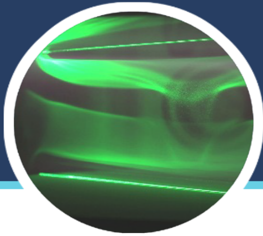
2 failed peaks



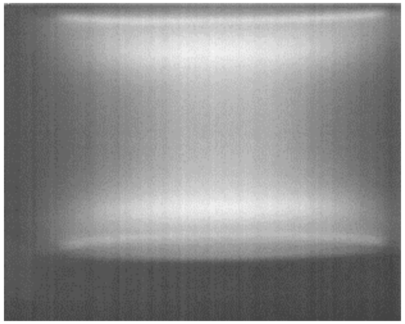
1 failed peak



M. Mikikian, L. Couëdel, M. Cavarroc, Y. Tessier, L. Boufendi, Phys. Rev. Lett. **105**, 075002 (2010)



HEARTBEAT INSTABILITIES: LAST BEATS…



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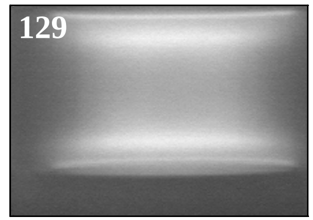
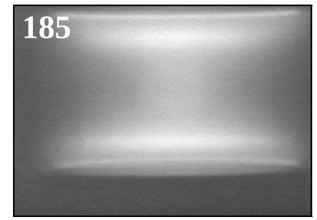
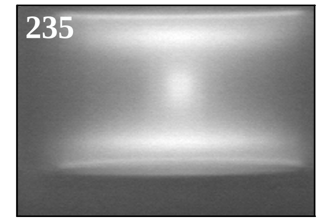
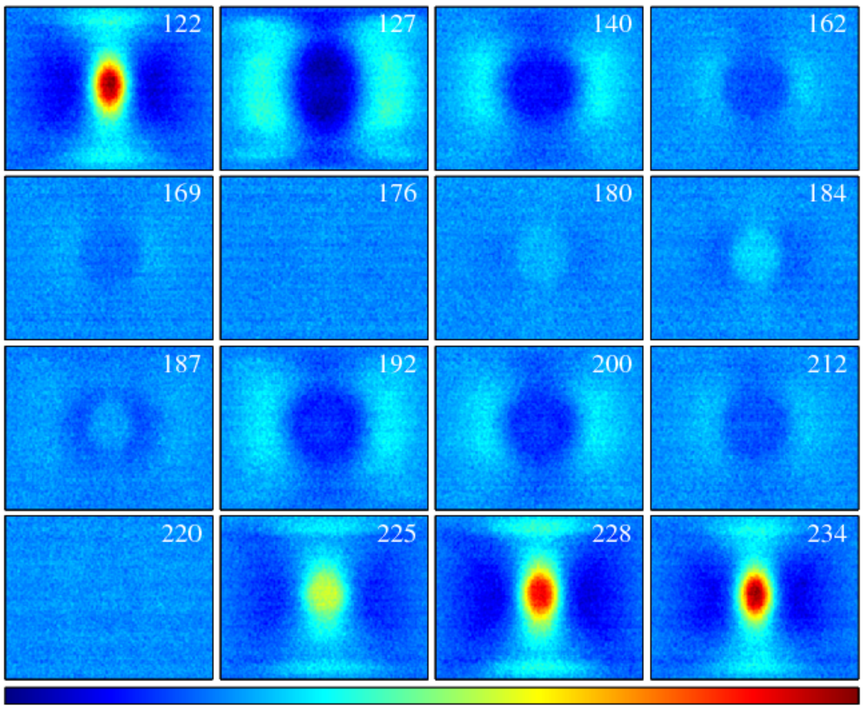
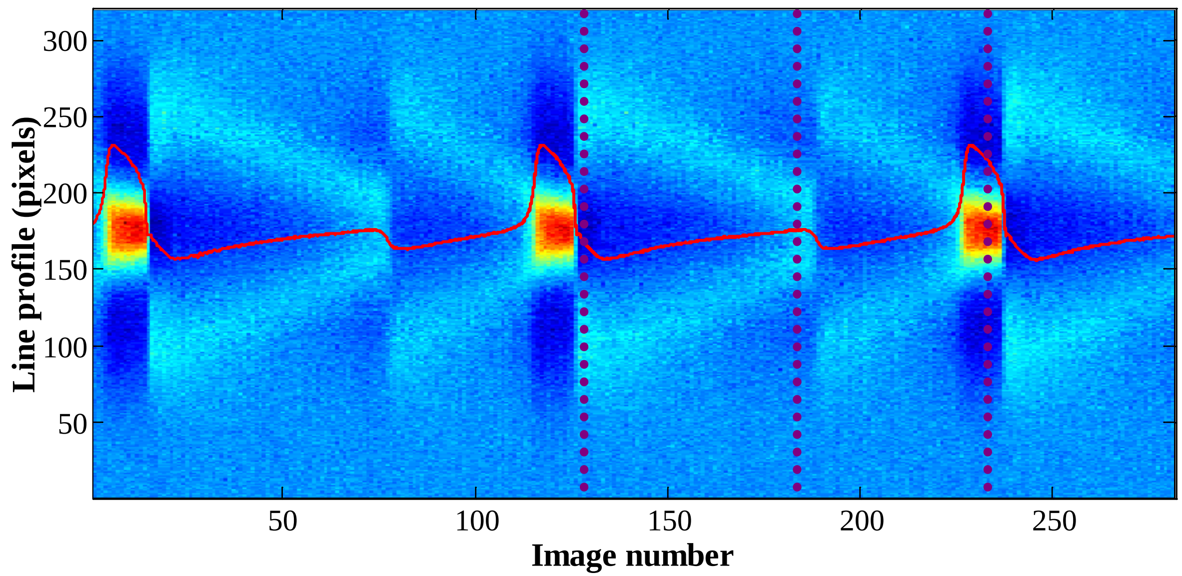




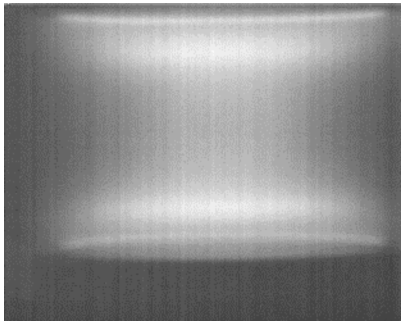






M. Mikikian, L. Couëdel, M. Cavarroc, Y. Tessier, L. Boufendi, Phys. Rev. Lett. **105**, 075002 (2010)

HEARTBEAT INSTABILITIES: LAST BEATS…



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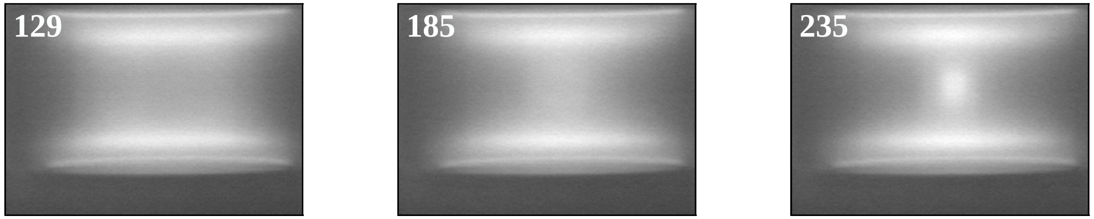

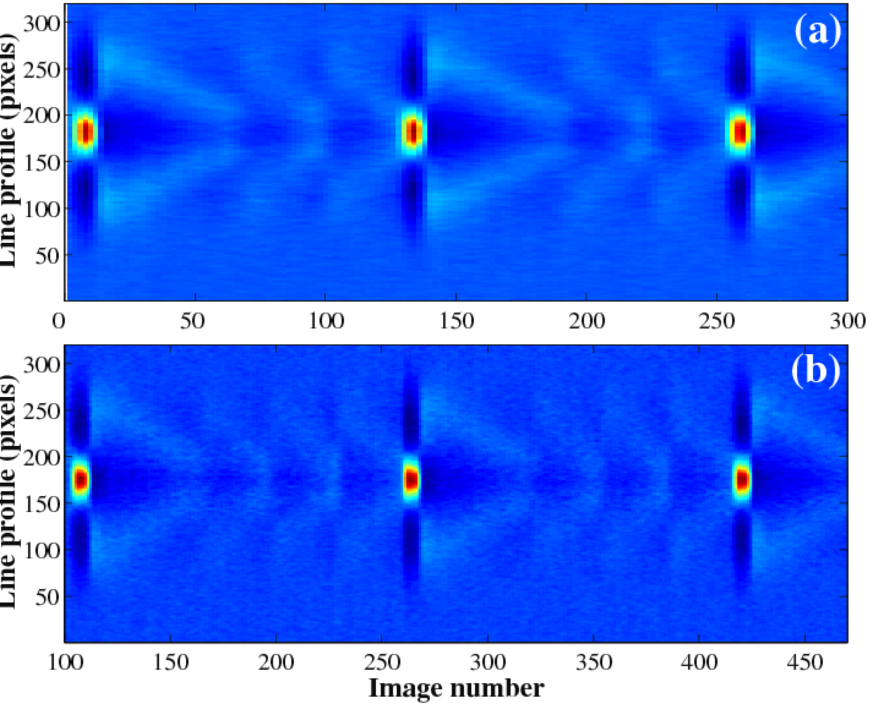

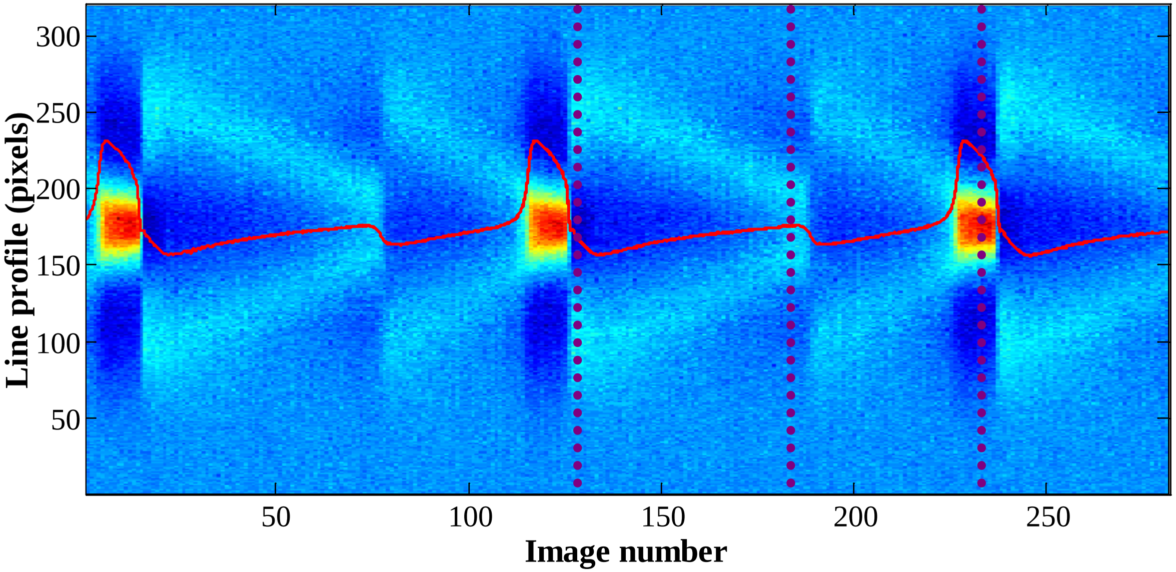

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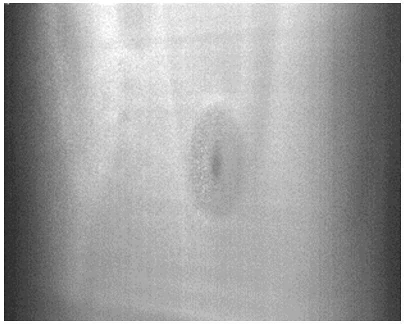
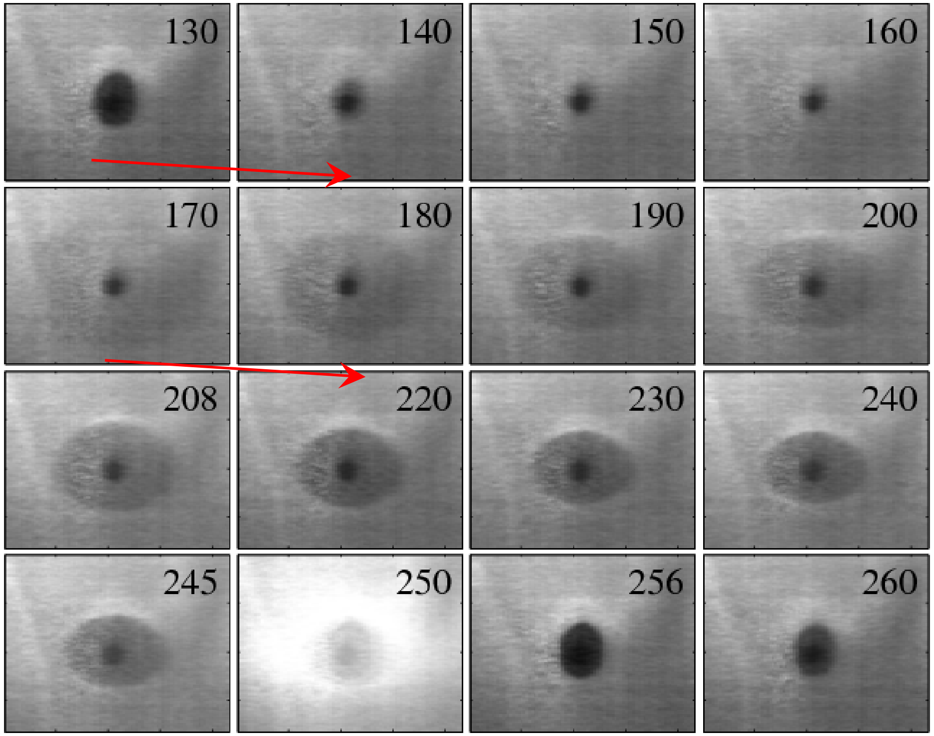
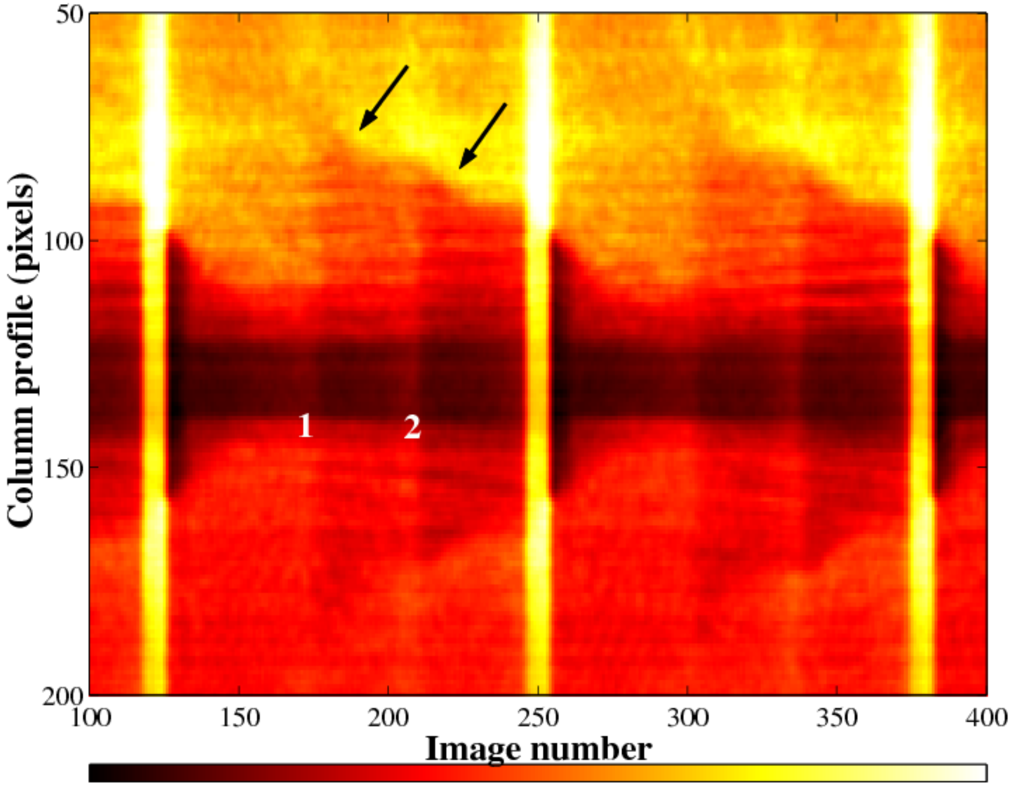
HEARTBEAT INSTABILITIES: LAST BEATS…





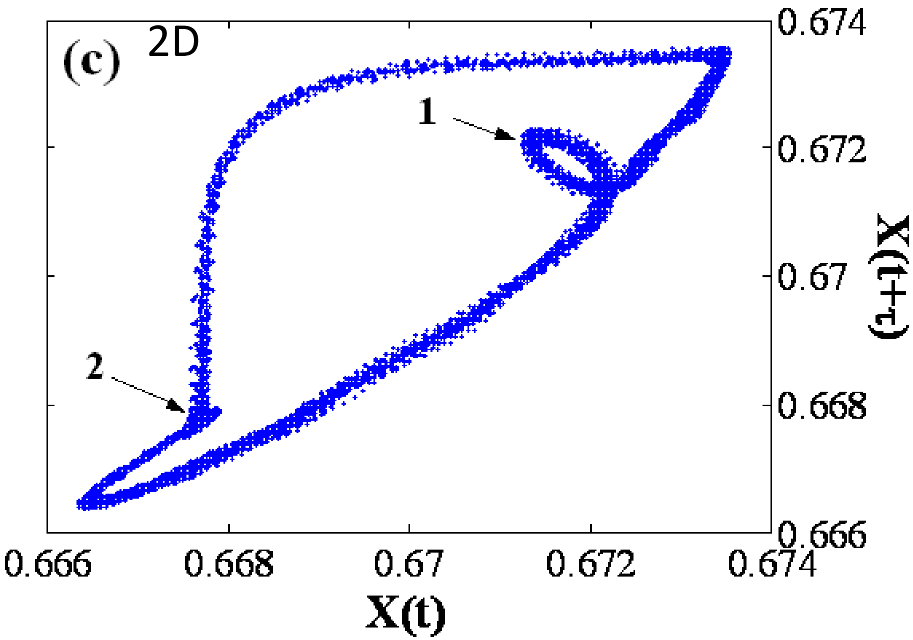
Central column profile with 2 failed peaks

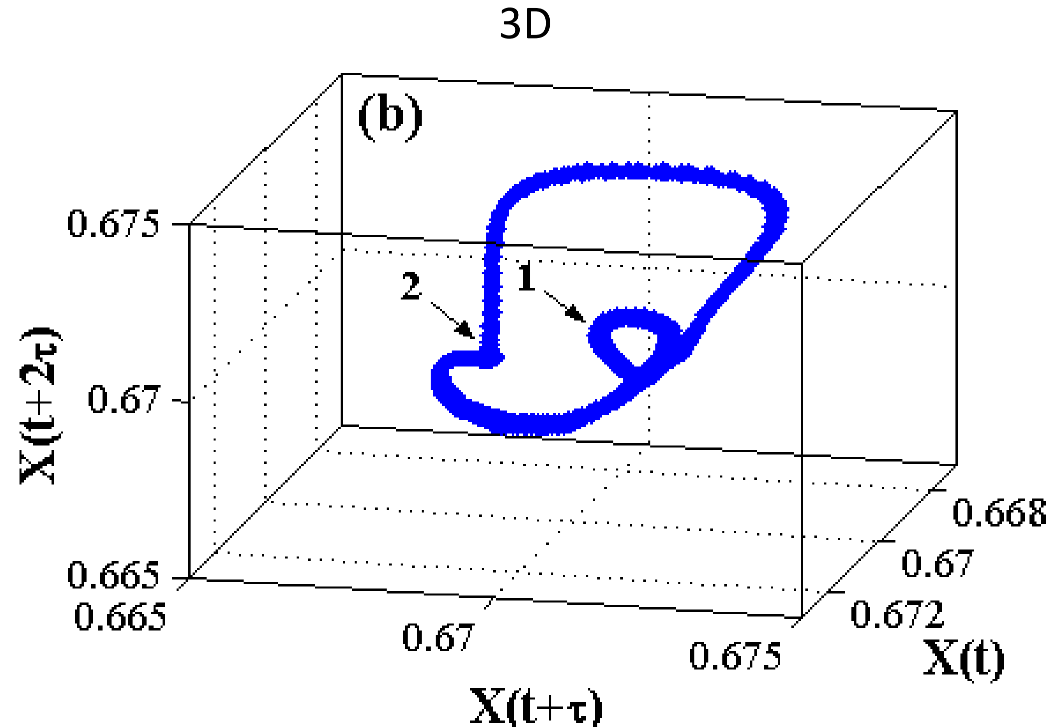


M. Mikikian, L. Couëdel, M. Cavarroc, Y. Tessier, L. Boufendi, Phys. Rev. Lett. **105**, 075002 (2010)

HEARTBEAT INSTABILITIES: LAST BEATS…

Phase Space X(t+τ) versus X(t)





Number of tiny loops in point 2 corresponds to the number of small amplitude oscillations

Large loops correspond to spikes

M. Mikikian, M. Cavarroc, L. Couëdel, Y. Tessier, L. Boufendi, Phys. Rev. Lett. **100**, 225005 (2008)

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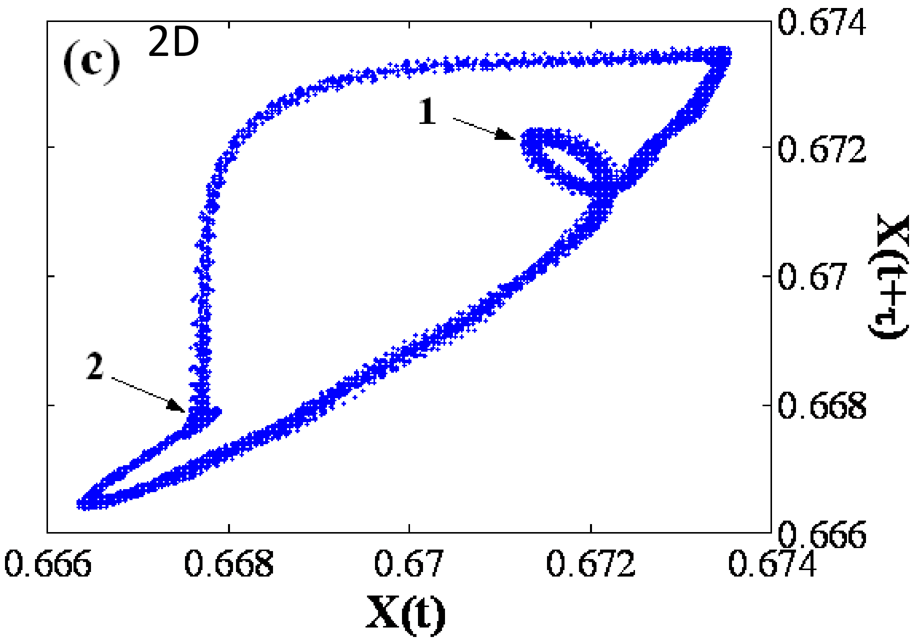

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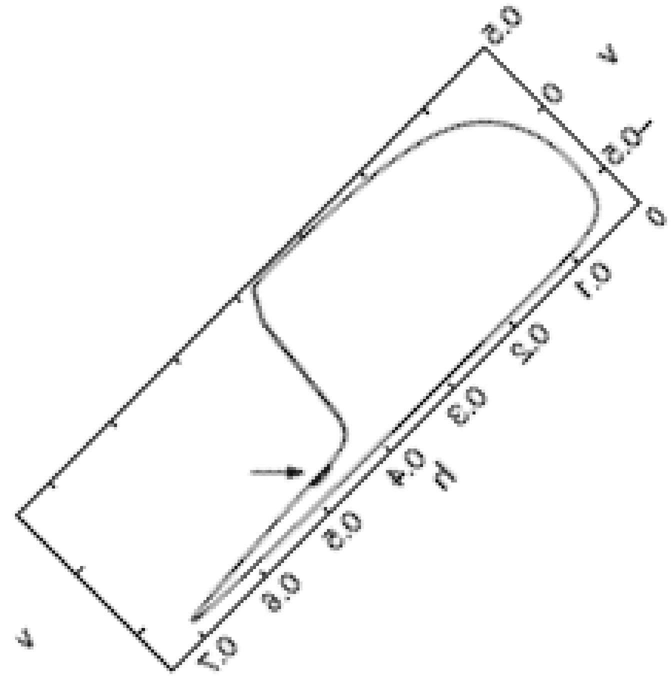
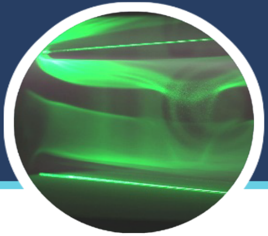
MMOs in Hodkgin-Huxley model of squid giant axon, Rubin et al., Biol. Cybern. (2007)



M. Mikikian, M. Cavarroc, L. Couëdel, Y. Tessier, L. Boufendi, Phys. Rev. Lett. **100**, 225005 (2008)

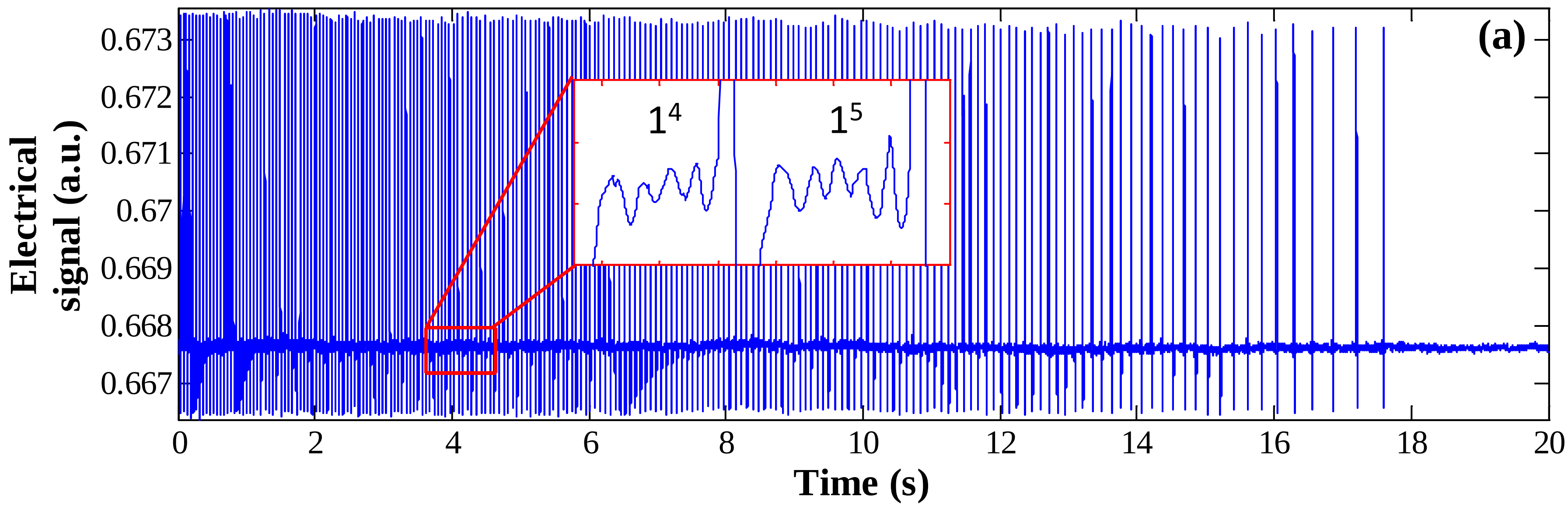


MIXED-MODE OSCILLATIONS

Failed peaks are more and more numerous as the instability end approaches

Transitions between L^S and L^{S+1} states

Very close to the end, transitions between L^S and L^{S+n} states with n from 2 to 5
→ Increasing period in between spikes



M. Mikikian, M. Cavarroc, L. Couëdel, Y. Tessier, L. Boufendi, Phys. Rev. Lett. **100**, 225005 (2008)

M. Mikikian, H. Tawidian, T. Lecas, O. Vallée, Comptes-Rendus 15ème Rencontre du Non-Linéaire, Paris, 15-16 mars 2012, éd. E.Falcon, C.Josserand, M.Lefranc, C.Letellier, Non Linéaire Publications, p. 145-150

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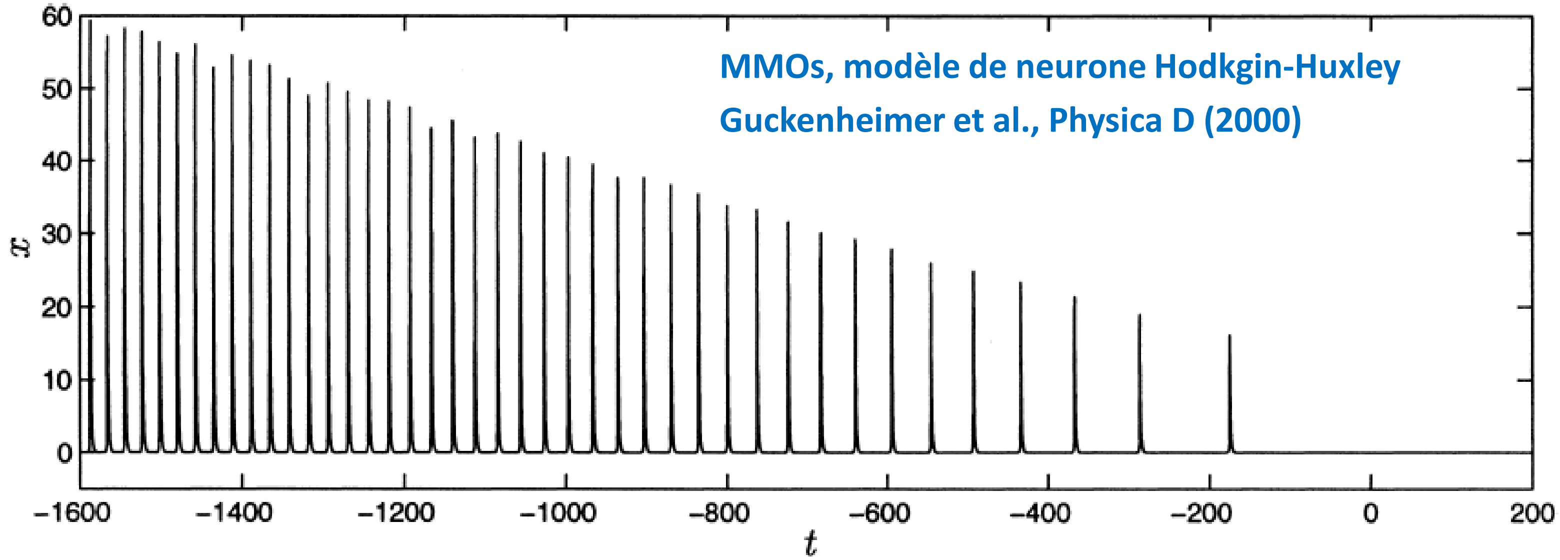

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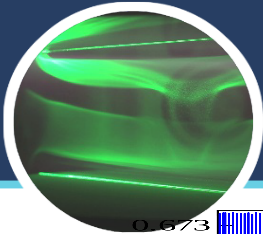
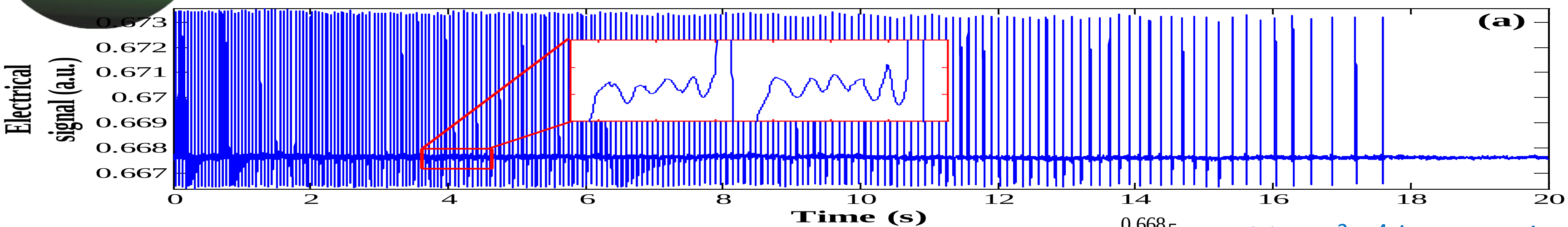
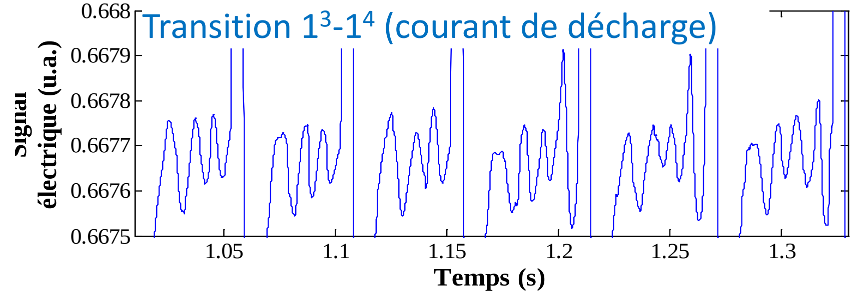
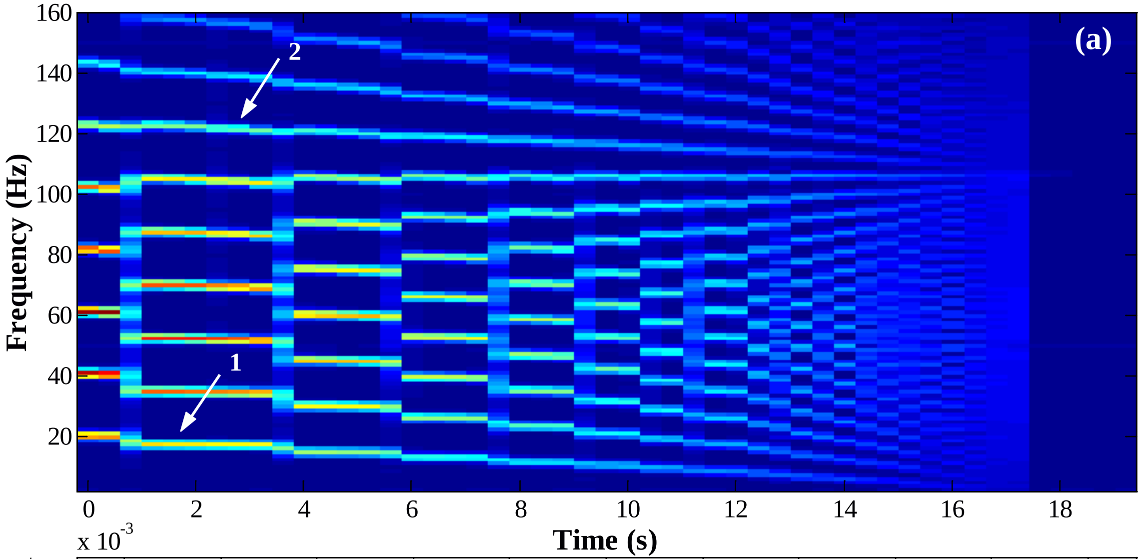
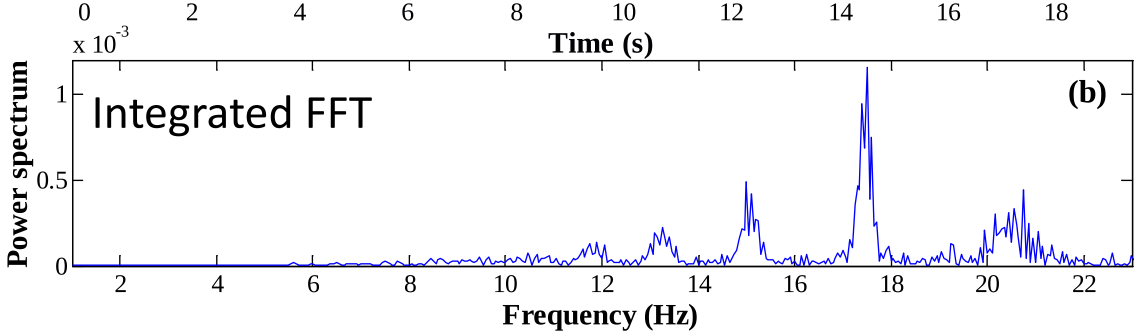


HEARTBEAT INSTABILITIES: LAST BEATS…









Temporal evolution of the frequency

→ Spectrogram

Main spike frequency (1)

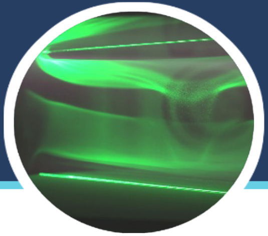
Small amplitude oscillation frequency (2)

Due to occurrence of more and more failed peaks, decrease by steps of :

Spike frequency

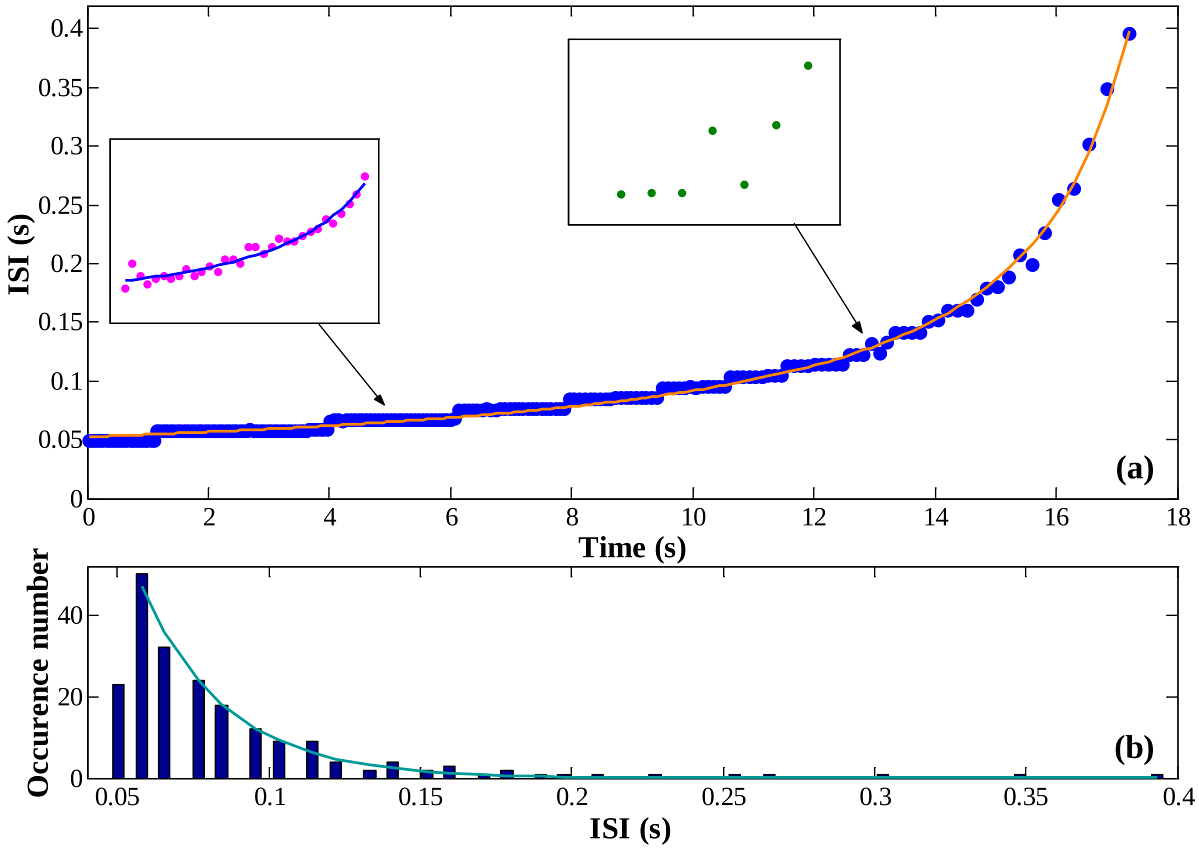
Duration of each new L^S state

M. Mikikian, M. Cavarroc, L. Couëdel, Y. Tessier, L. Boufendi, Phys. Rev. Lett. **100**, 225005 (2008)



HEARTBEAT INSTABILITIES: LAST BEATS…

Statistics on Interspike intervals is often used in neuroscience for characterizing neuronal activity

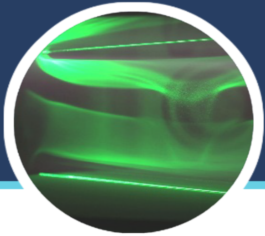


ISI increases as the end approaches (frequency decreases)

Each L^S state is characterized by a small but progressive increase of the ISI

Transition to a new L^{S+1} state occurs after the progressive increase of the ISI in the L^S state

Mikikian et al. Phys. Rev. Lett. **100**, 225005 (2008)



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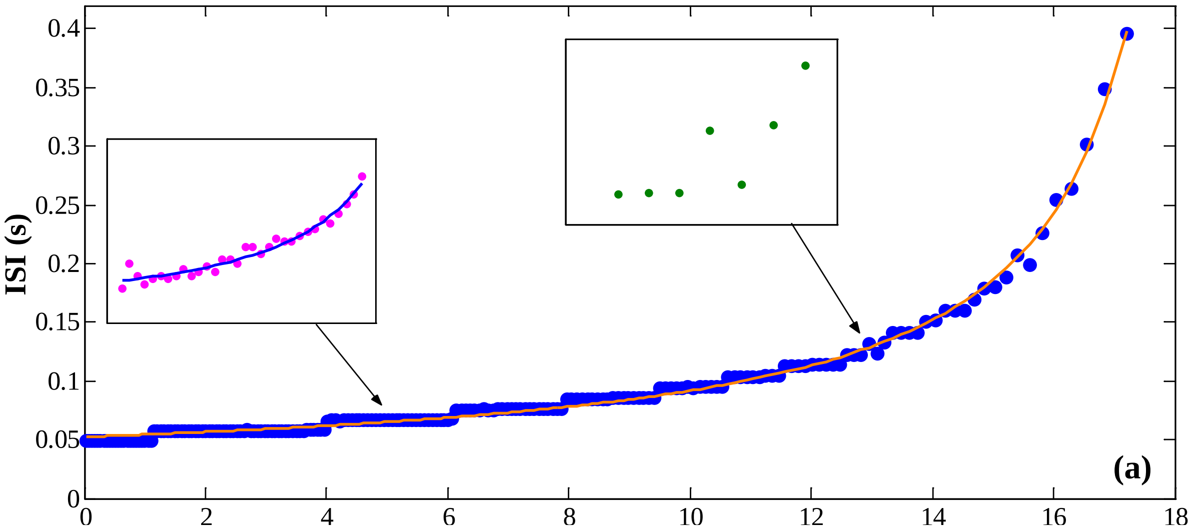

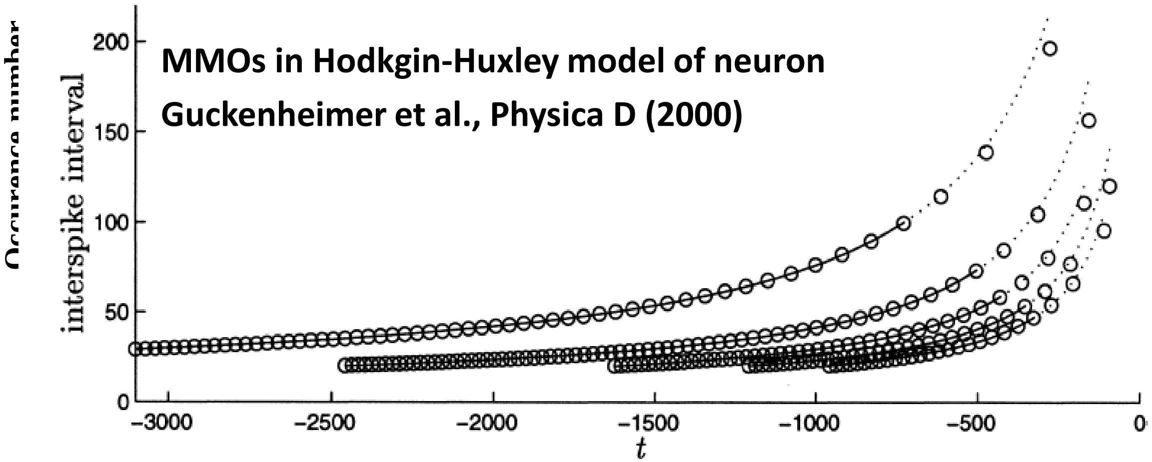

MMOs in Hodkgin-Huxley model of neuron

Guckenheimer et al., Physica D (2000)

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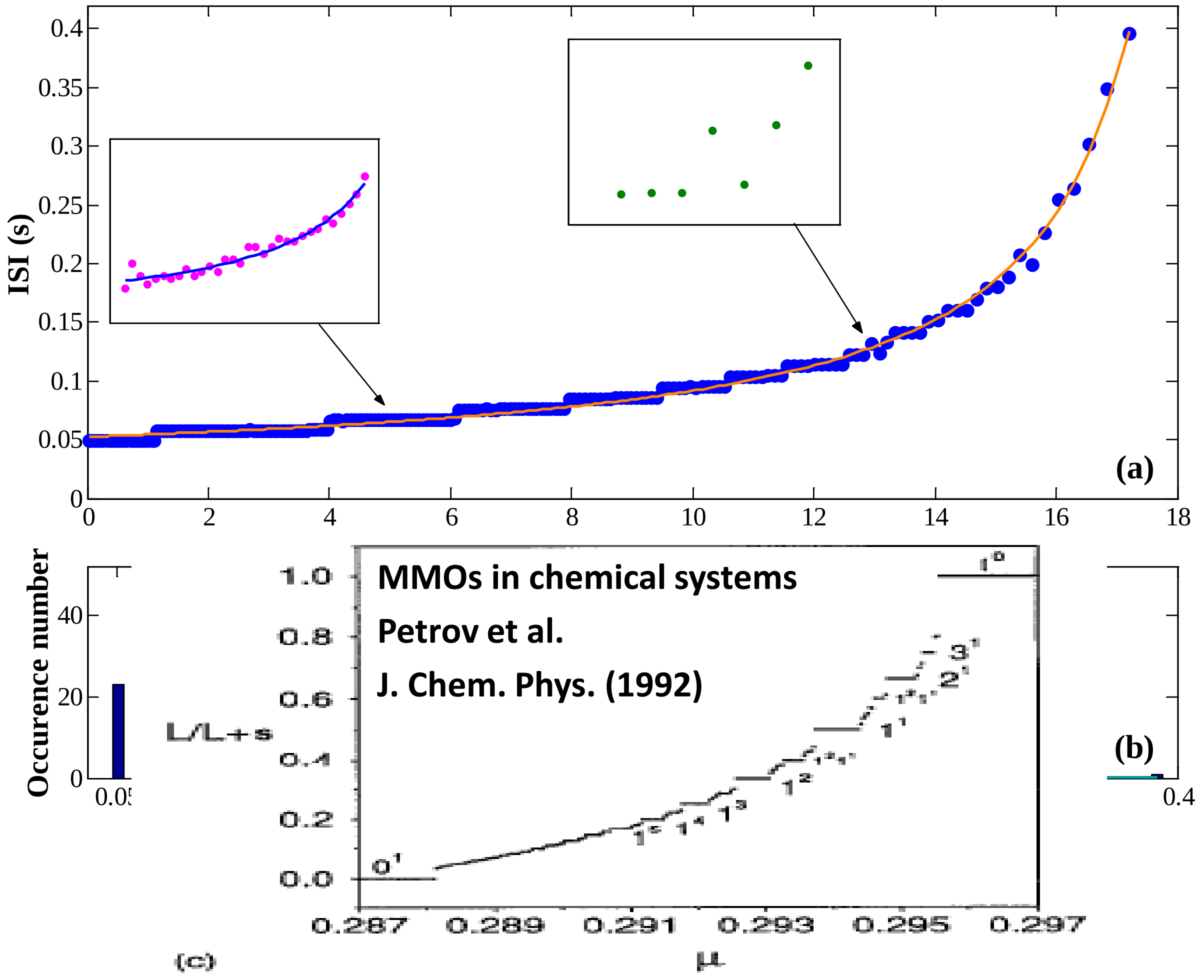


ISI increases as the end approaches (frequency decreases)

Step behavior in nonlinear systems :

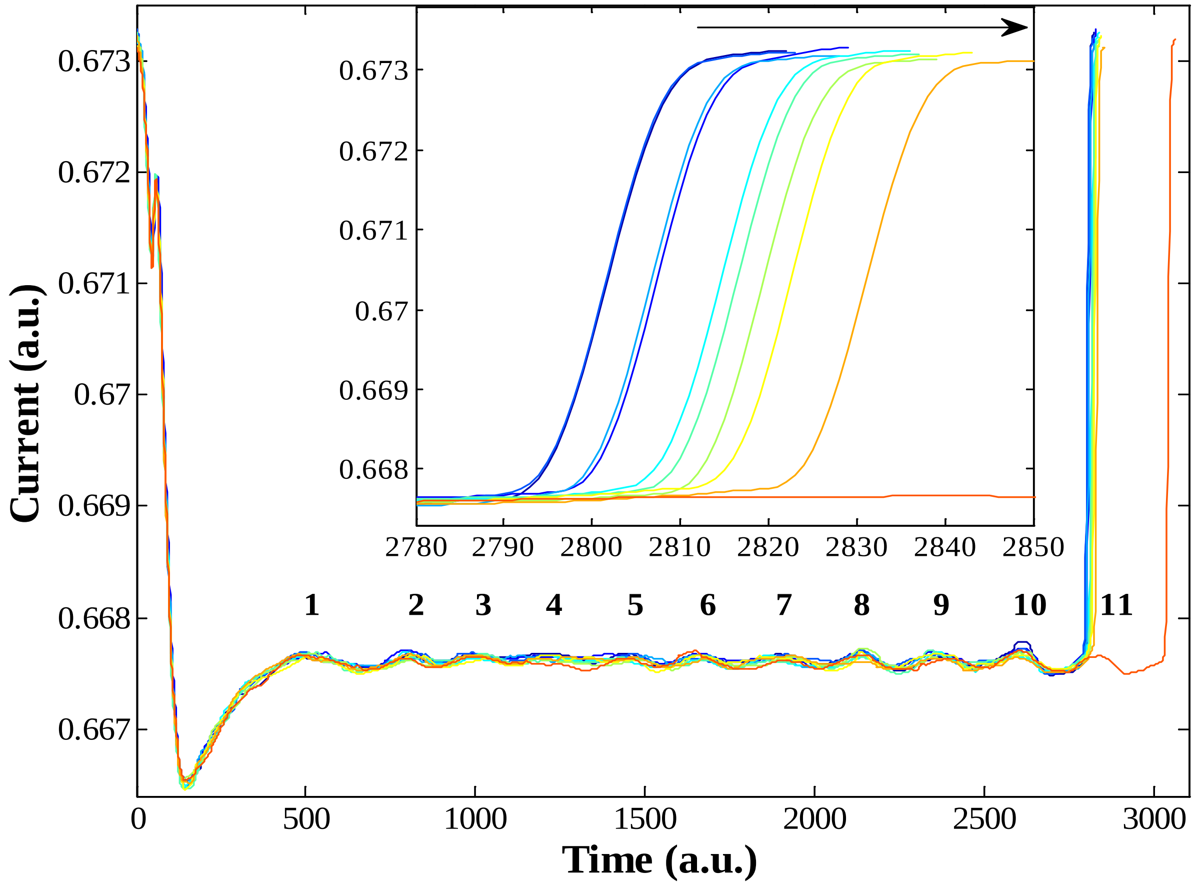
Devil's staircase

Farey trees

Mikikian et al. Phys. Rev. Lett. **100**, 225005 (2008)

HEARTBEAT INSTABILITIES: LAST BEATS…

Superimposition of states 1^{10} and transition to 1^{11}



M. Mikikian, H. Tawidian, T. Lecas, O. Vallée, Chaos, Complexity and Transport, Proc. CCT’11, éds. X. Leoncini, M. Leonetti, World Scientific Publishing, Singapore, p. 85-93 (2012)

HEARTBEAT INSTABILITIES: LAST BEATS…

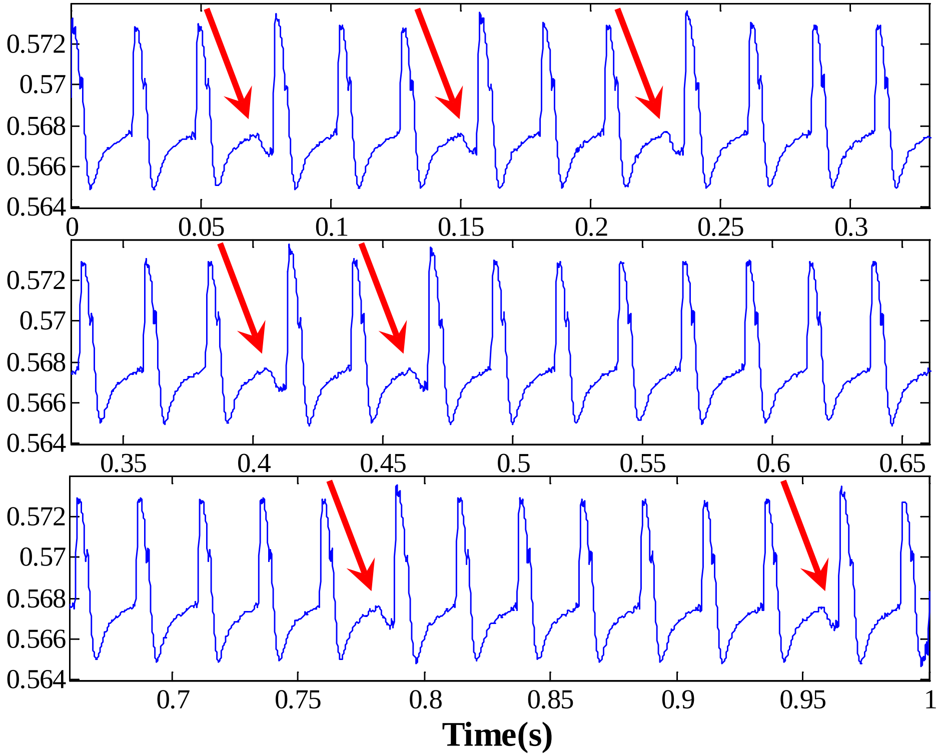
Alternation of two states differing by one failed peak

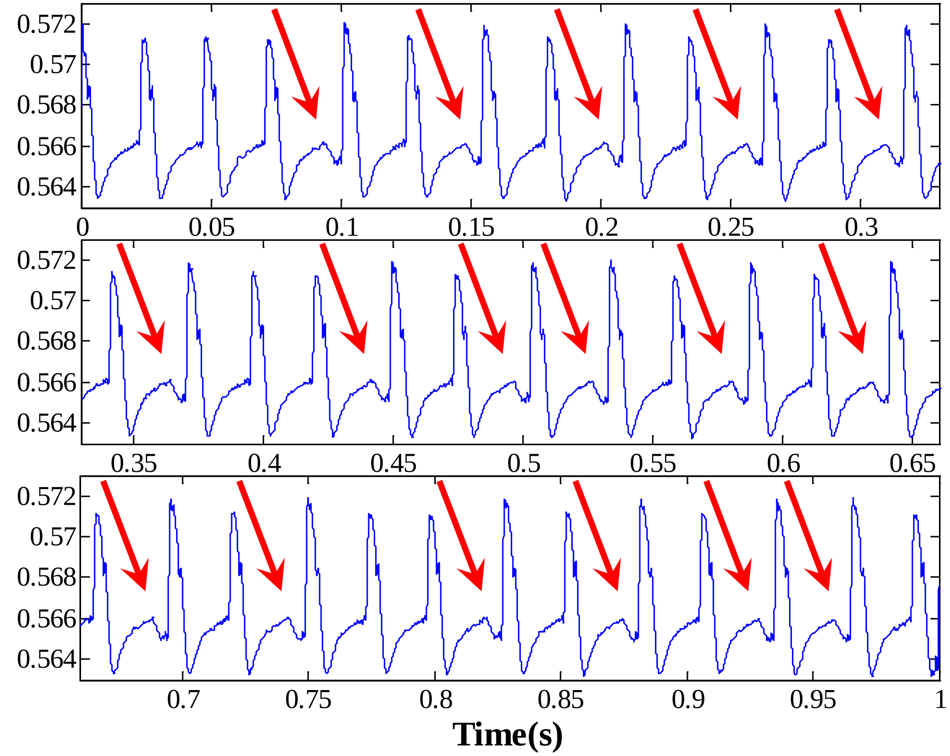
Progressive occurrence of L^{S+1} patterns during a L^S state

Incomplete devil's staircase

Intermediate states related to the parent states by the Farey arithmetic?

More intermediate states with slower varying signals to complete the staircase





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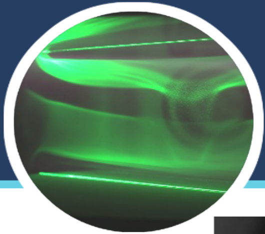
TO BE DONE FOR PERISTOCH

- **Reproduce the experiments and acquire more new data like MMO**
- **Evaluate the role of the external electrical circuit**
- **Find any dependence with the signal amplitudes (thresholds?) or with the noise level**
- **Determine a set of equations modelling main void characteristics: from existing void theories or from existing MMO models**
- **Comparisons modeling/experiments**



THANK YOU !