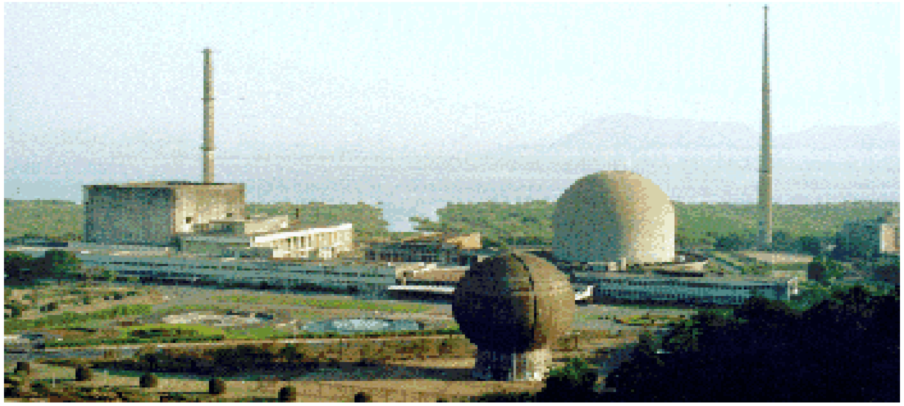
New directions in monitoring & feedback control in high power plasma processing devices

A.K. Das



BHABHA ATOMIC RESEARCH CENTRE

Trombay, Mumbai-400085

Contents

- Processing plasmas, an introduction
- Issues in monitoring and control
- Origin of fluctuations and instabilities in processing plasmas
- Experiments, analysis and a generalized predictive theory for fluctuations
- Possibility of monitoring & control
- Conclusions

B
A
R
C

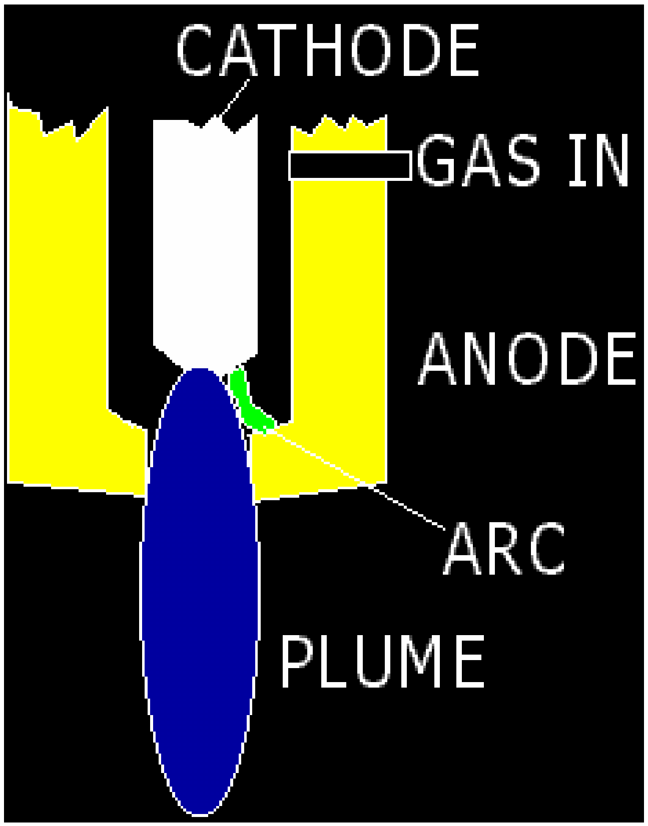
Processing Plasmas

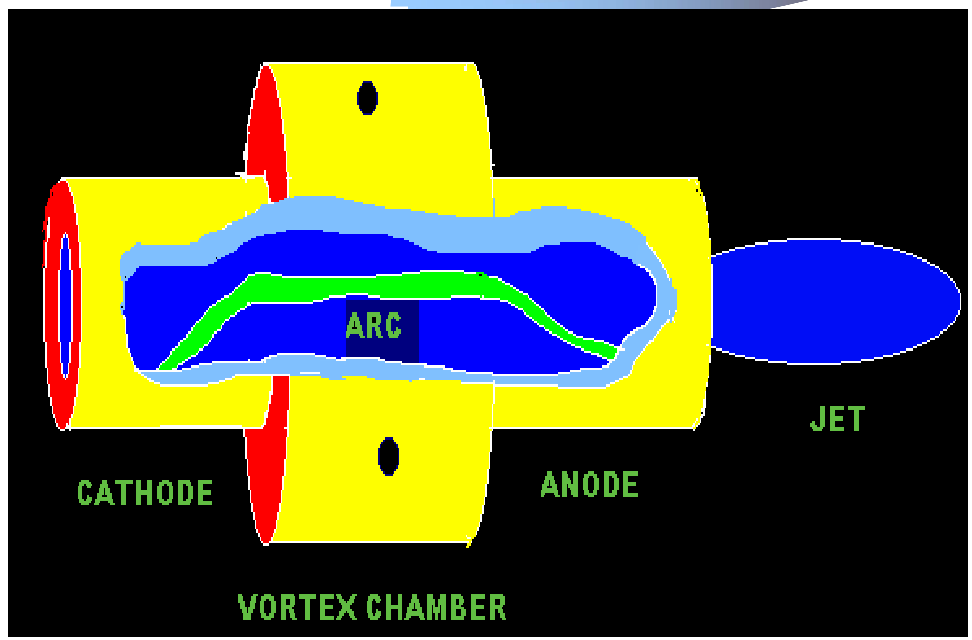
Low temperature plasmas for materials processing applications

- **Plasma spraying**
- **Wire arc spraying**
- **Plasma CVD**
- **Plasma synthesis of powders**
- **Toxic waste destruction**
- **Spheroidization**
- **ADSS Simulator**
- **Plasma melting**
- **Plasma extractive metallurgy**
- **Nano-particle & nano-tube generation**
- **Space reentry simulation**

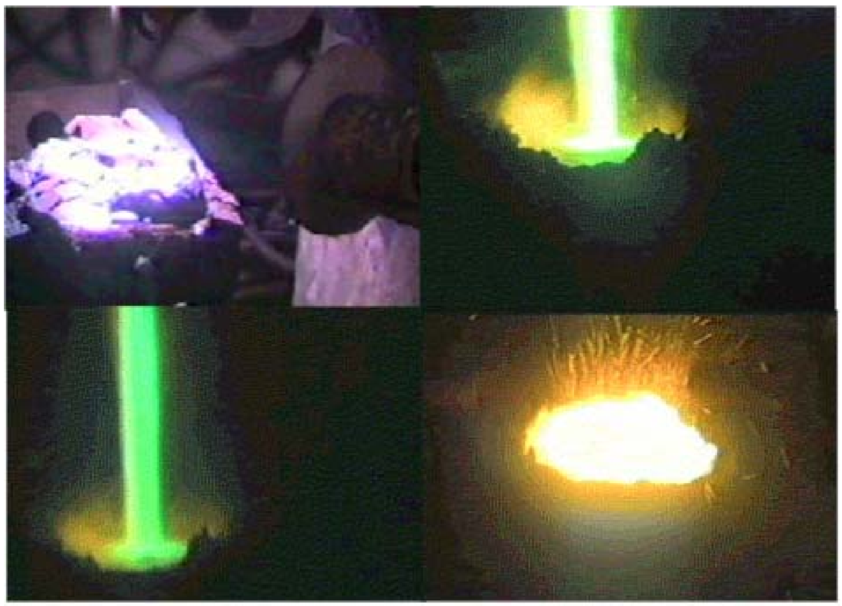
B
A
R
C

A look at typical plasma generators that form heart of these applications

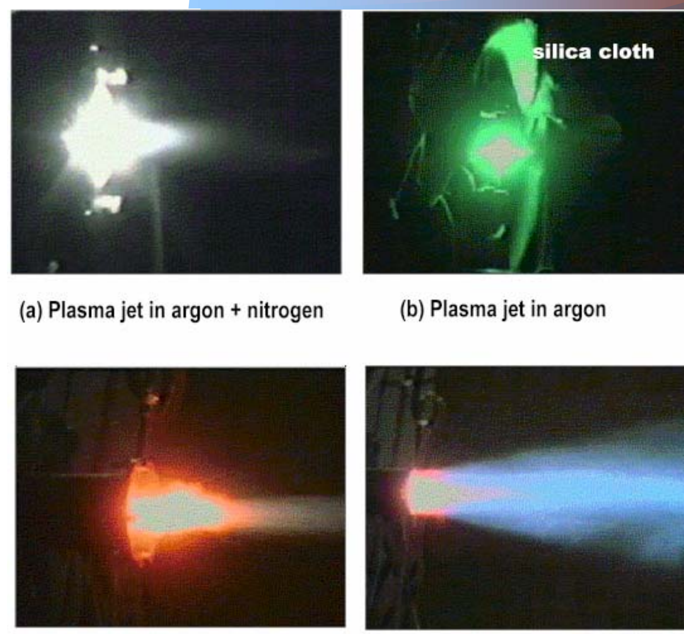




Plasma Generators and jets



PLASMA MELTING OF METALLIC SCRAP



(a) Plasma jet in argon + nitrogen

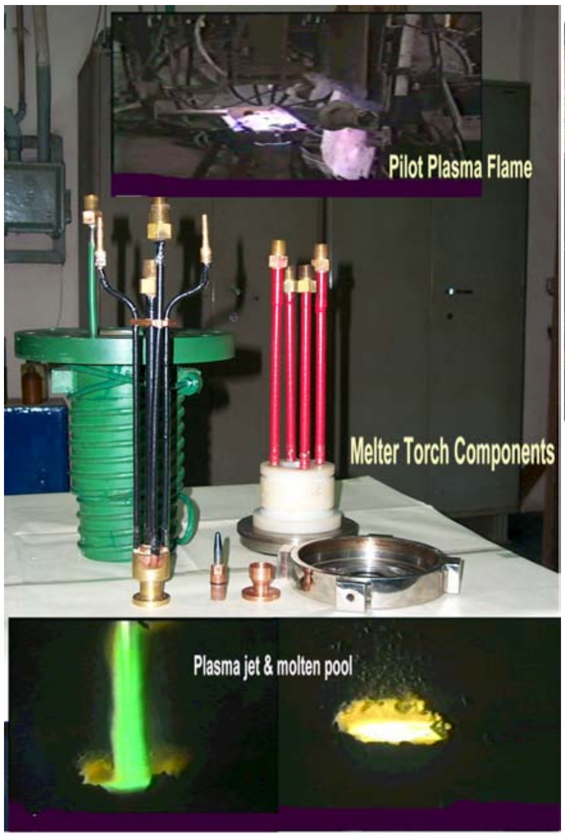
(b) Plasma jet in argon

(c) Plasma jet through graphite nozzle

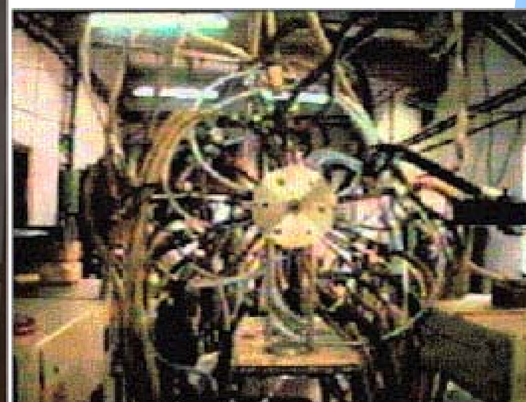
(d) Powder laden plasma jet

CONSTRICTOR ARC PLASMA JET DEVICE

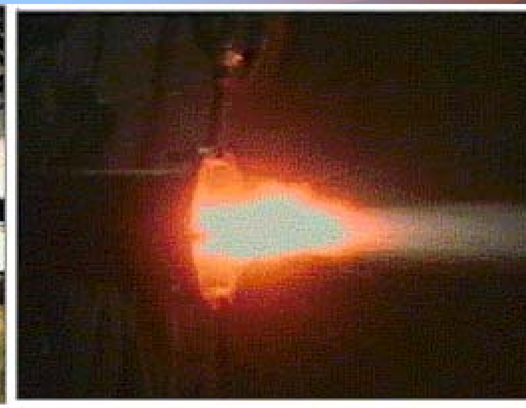
Plasma Generators, jets, fluctuations



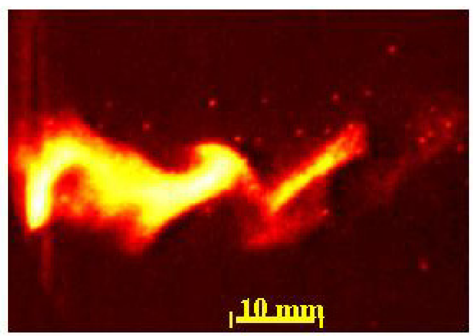
300 kW Plasma Melter Developed at BARC

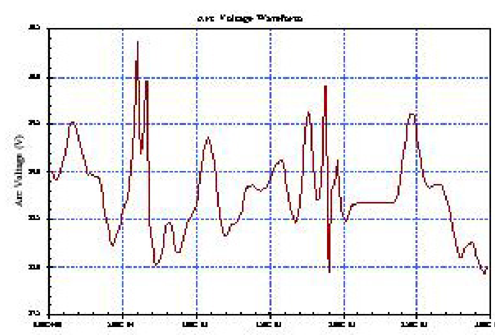


(a) plasma tube (14 ring)



The Constrictor Arc Plasma Jet





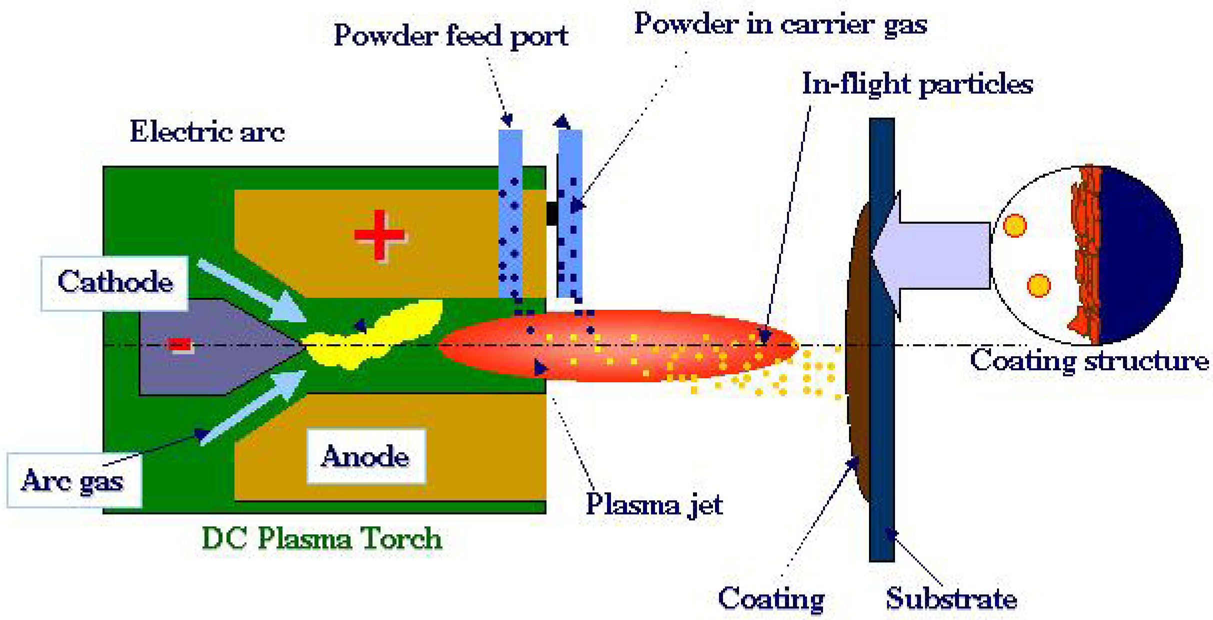
Major concerns in plasma processing

- Problem
- **Large number of independent variables make process control difficult**
- **Plasma jet instabilities and arc fluctuations reduce coating reproducibility**
- **Short device life time**
- **Poor efficiency**
- **Unreliable performance**
- **Uncontrolled electrode erosion**

Action Point

- **Predictive computer models for torch, plasma jet and particle interactions**
- **Virtual process simulation**
- **Predictive codes and analysis of arc fluctuations**
- **Similarity analysis in tandem with experiments**
- **Real time monitoring and control functions**

Case Study 1 – Plasma Spray Processing

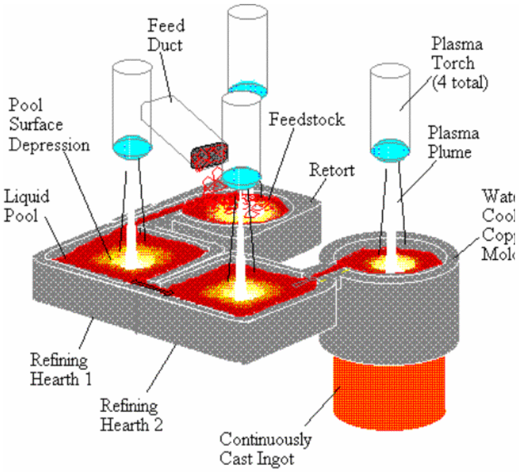


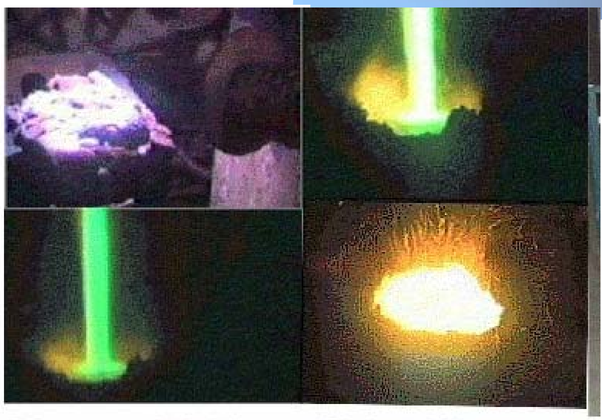
The plasma jets fluctuates resulting in unmelts, cold gas entrainment and low, unreliable deposition efficiencies

Major action points in Plasma spray monitoring and control protocol

- improve the torch stability
- control on-line the wear of the electrodes
- control the gas flow around the spray jet and close to the substrate
- study `in flight' chemical reaction as well as particle vaporization and resulting vapor condensation
- A better understanding of coating formation (particle impacts and resulting splats layering)
- Create a database for building a feedback control strategy

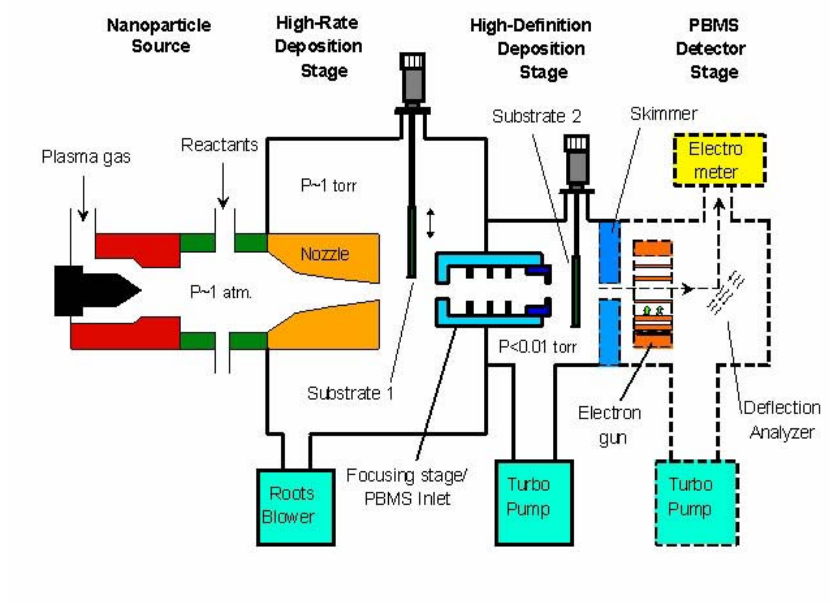
Case Study II – Plasma Melt Processing




Plasma Melting of Metallic scrap

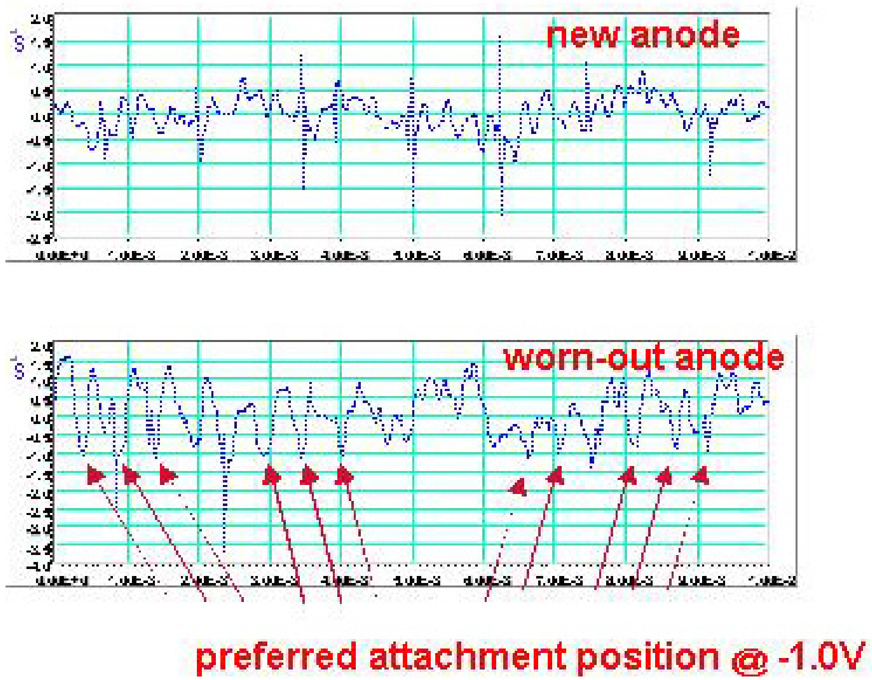
Spatio temporal heat delivery & melting efficiency severely affected by instabilities

Case Study III – Processing of sub micron particles



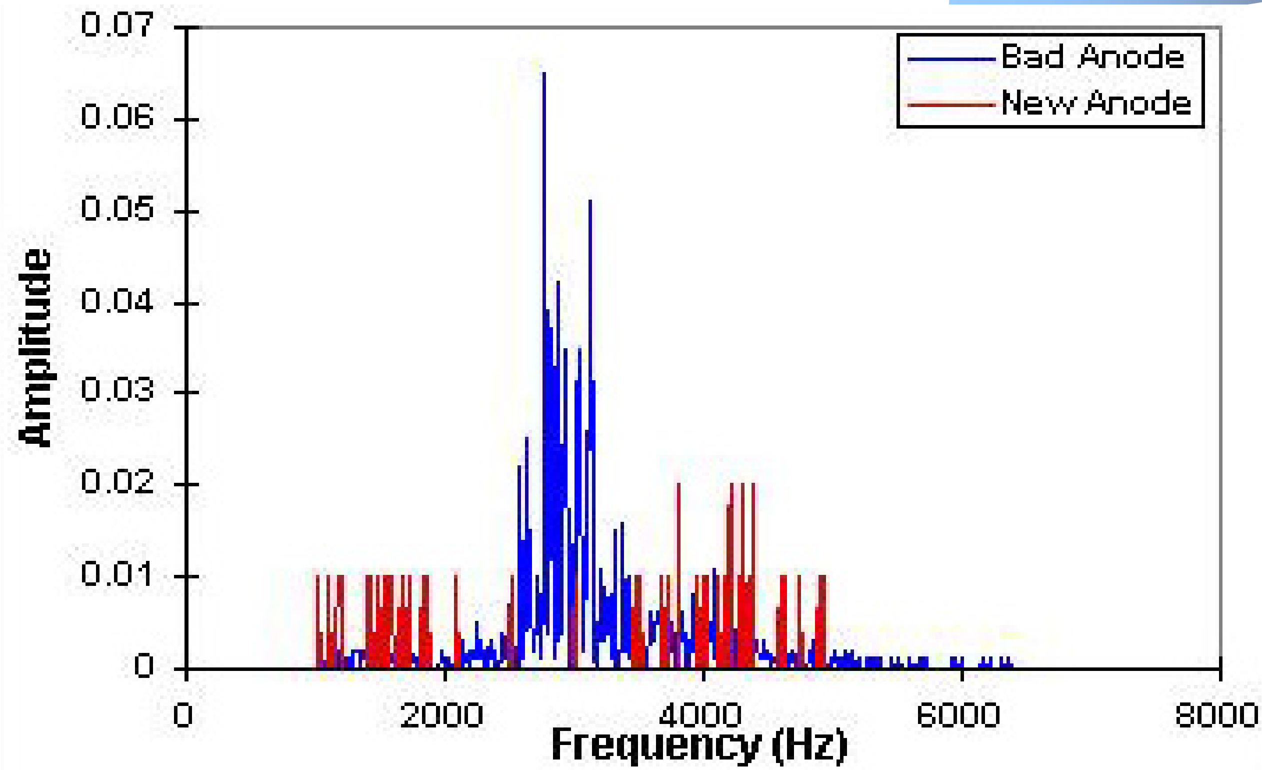
Plasma jet fluctuation induces fluctuations in plasma temperature resulting in generation non uniform powders

Arc fluctuations (voltage trace) carry signature of Device conditions

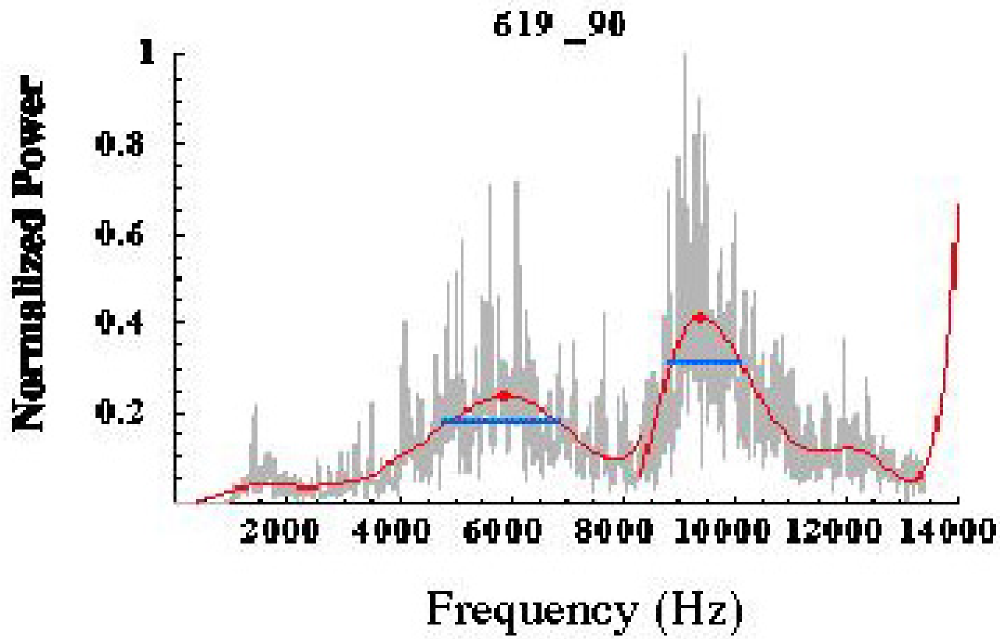


Voltage traces obtained with different anodes

Arc fluctuations (Power Spectra)carry signature of Device conditions



Arc fluctuations (Power Spectra)carry signature of Device conditions



Power spectrum of plasma jet acoustic signal shows two groups of frequency peaks (high ratio between two peaks is an indicator for bad torch performance

Current State – Technology Driven Research

Understanding and controlling

- ***The arc root instability***
- ***Erosion of electrodes***
- ***Fluid dynamic instability of the plasma jet interacting with the active environment.***

Development of

- ***Control functions to establish automatic feedback control***
- ***Generalized theory of plasma jets including arc root***
- ***Comprehensive database and correlations between the plasma as well as system variables.***

Instabilities (uncontrolled growth of infinitesimal perturbations) in Arc Plasma jets

- Electrical Instability : origin in negative arc characteristics
- Thermal instability: origin in sudden heating or cooling of the plasma
- Fluid dynamic & MHD Instabilities: Origin in mixing, demixing and spatial growth of perturbations in self consistent field
- Arc root instabilities: origin in multi-scale shunting of arc and fluctuations in physical parameters

Arc root is at the root of it all

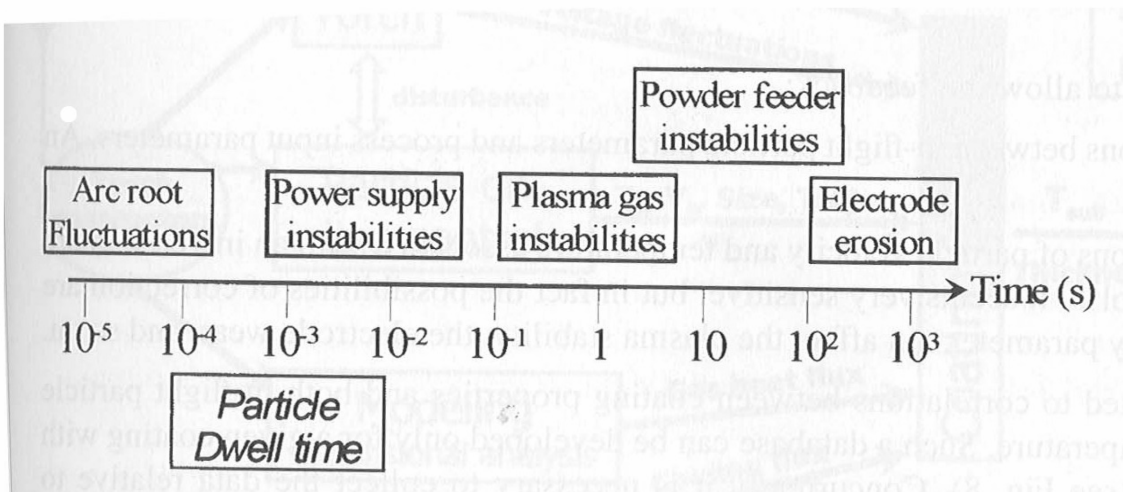


Fig. 5 Main instability frequencies in plasma processing

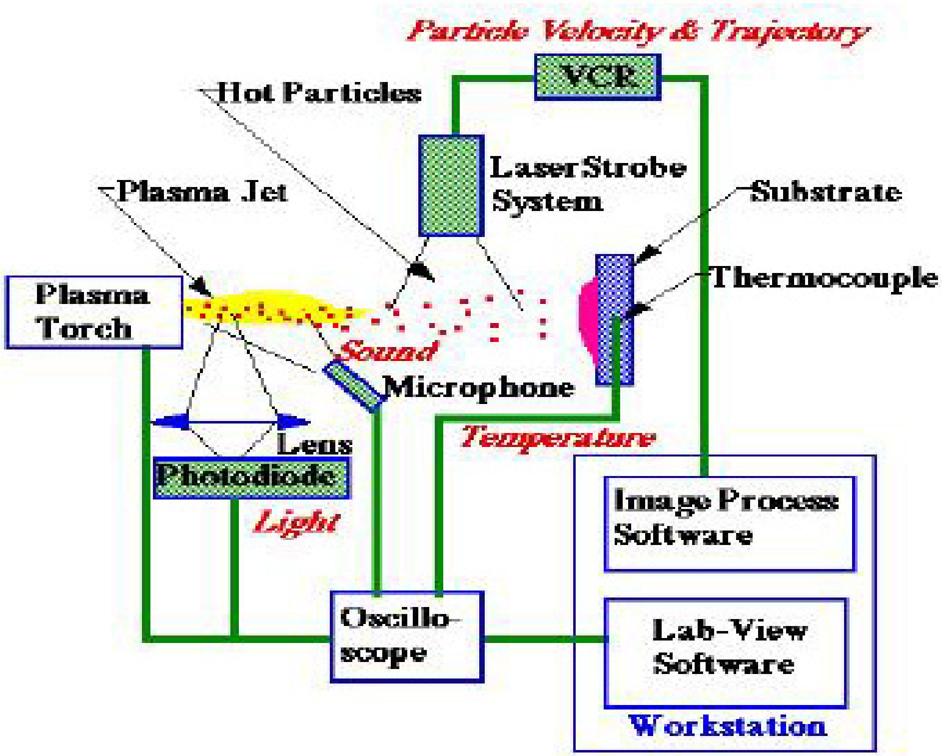
Characterization of Fluctuations through Nonlinear Dynamics

- Arc Instabilities manifest through fluctuations in Electrical or voltage, Optical and Acoustic
- Tools of Nonlinear Dynamics :
- Time Series
- Power Spectra: periodicity
- Quasi-periodic and periodic : distinct spikes
- Random signals : continuous broadband spectra.
- Chaotic: continuous, broadband spectra with spikes
- Phase portrait and attractor structure : set of trajectories in phase space
- Dimension and Fractal dimension : rate of information flow from the system
- Lyapunov Exponent : divergence of nearby trajectories in phase space with time
- Control parameters : physical parameters governing transition between dynamic states

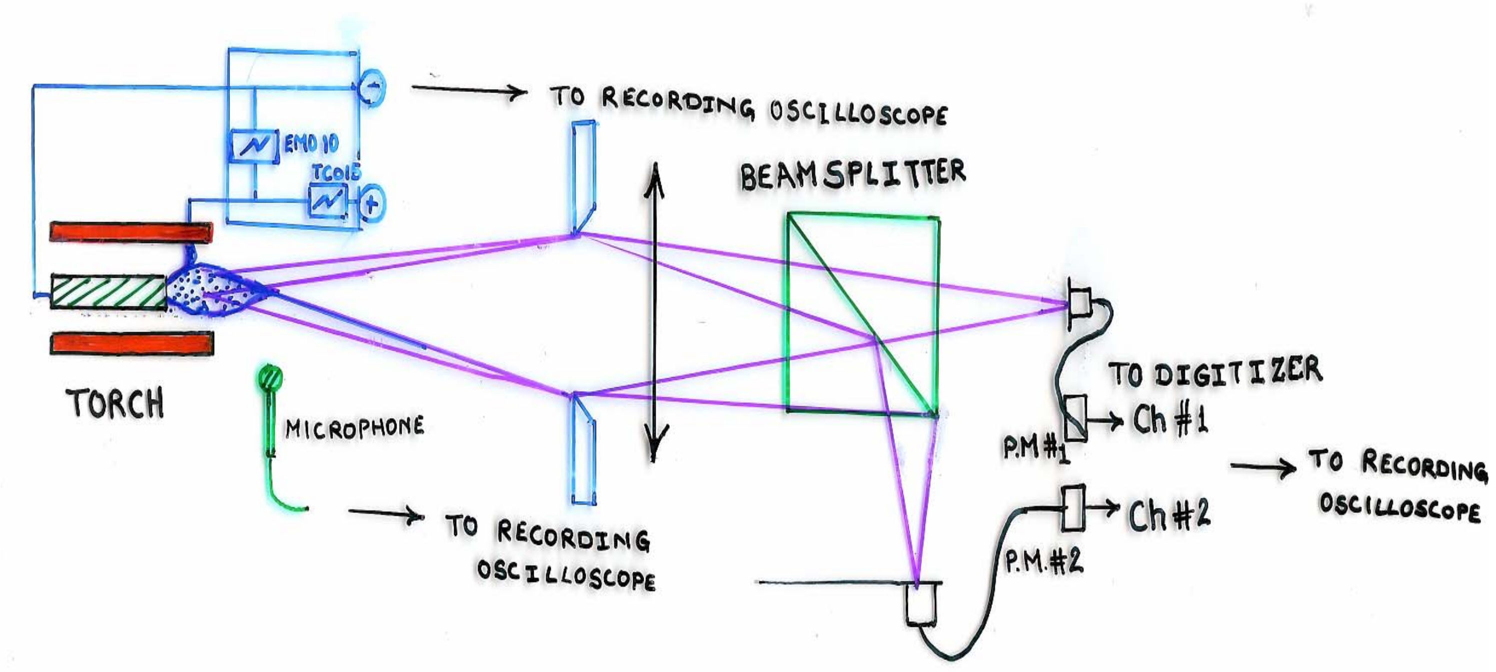
Chaos, what is it ?

- **All physical systems fall under the category of being periodic, random or chaotic**
- **Chaos is a kind of order (invariance with scaling) without periodicity**
- **Characteristic phase space portraits called strange attractors**
- **Positive Liyapunov coefficient and fractal dimension**
- **A set of control parameters dictate chaotic transition**

Schematic of a monitoring & measurement system for plasma jets (Univ. Minn.)



Experimental Schematic



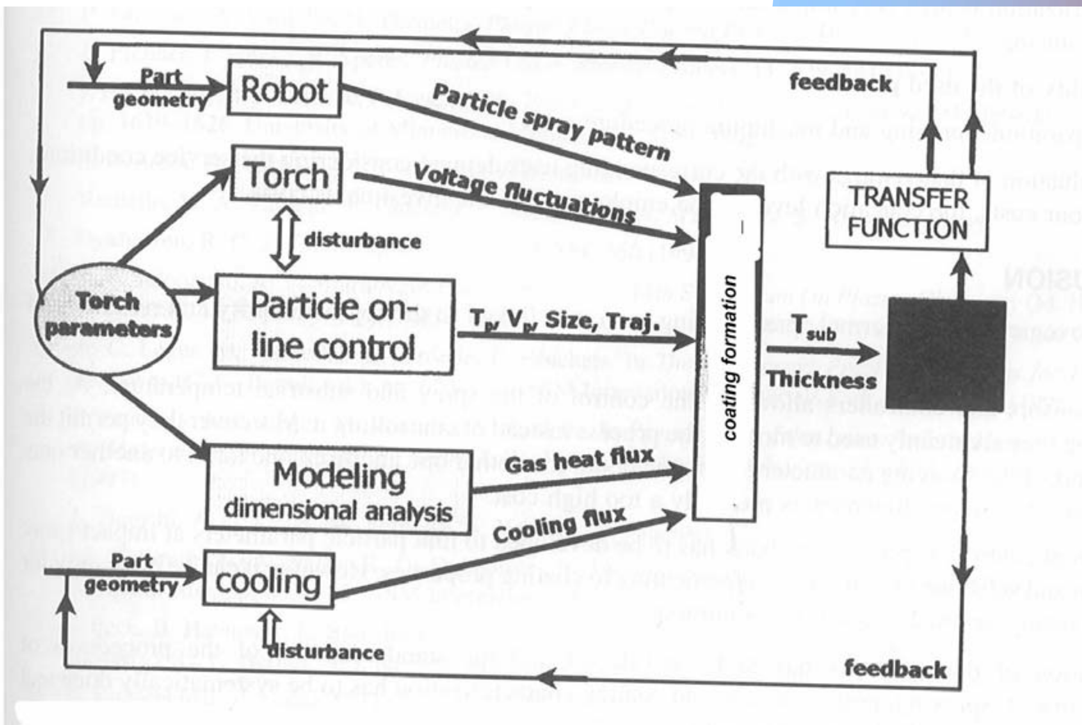
Experimental Parameters

- Voltage signal: the alternating component component measured using a Nicolet PRO-30
- Acoustic Signal: broad band 20 Hz. To 20 KHz. Microphone
- Optical Signal :PMT with large bandwidth
- Sampling time 2-5 micro sec.
- Sample length 10000-20000 points
- Currents 100-500A
- Arc power – 12 – 100 kW
- B field : 0.025 T
- Gas : argon 5 – 100 LPM

Time series - Post Processing

- Fast Fourier Transform with Radix-2, Cooley Tukey FFT algorithm
- Phase portrait with delayed coordinate construction at 15*del* T
- Dimension : A family of dimensions Capacity, correlation, information
- Largest Lyapunov exponent through wolf's algorithm with proper choice of length scale and evolution time and Dim for stationary L
- Correlation between synchronized signals

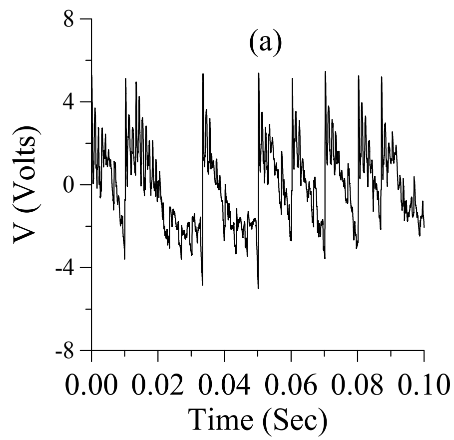
A suggested control protocol

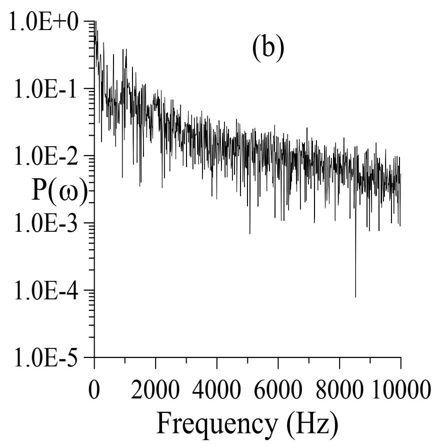


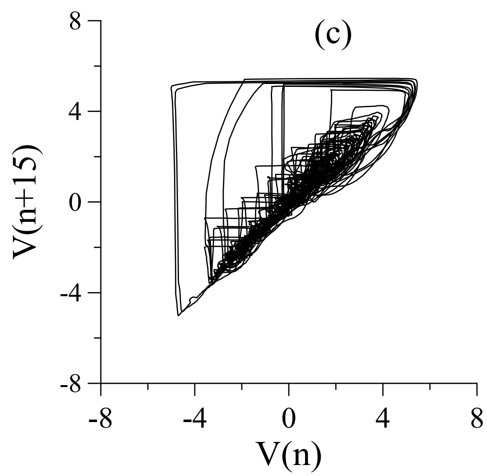
On-line feedback control strategy

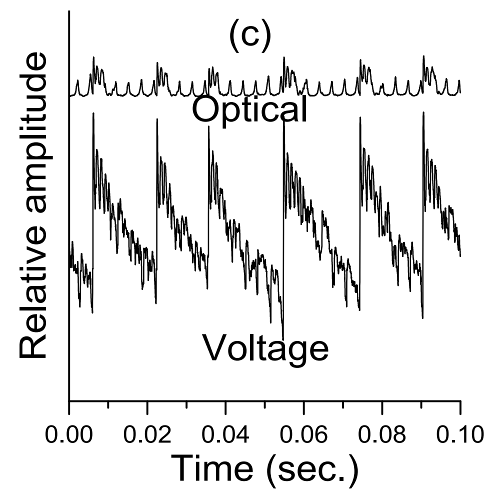
Reverse saw-tooth waveform with sudden and irregular amplitude jumps
Power spectrum is broad band and continuous with attractor structure as shown

Voltage Signal



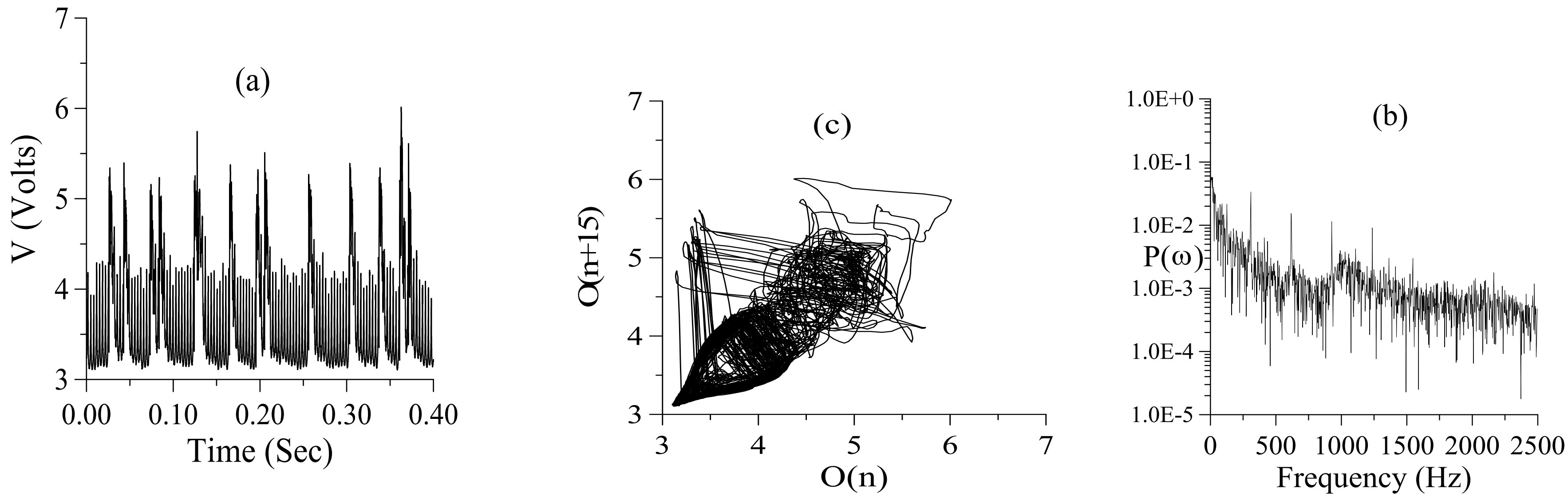






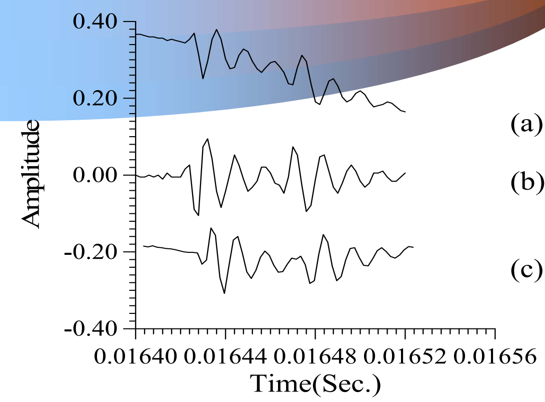
Optical Signal

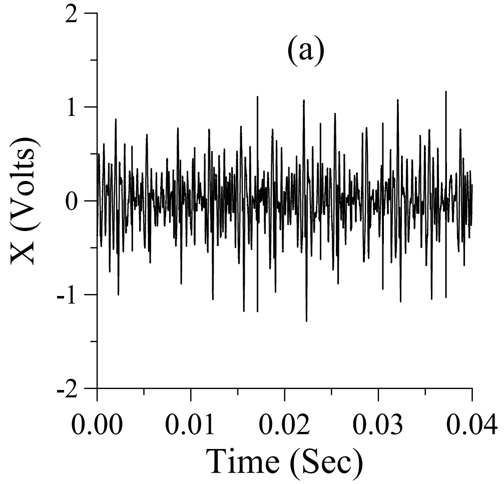
Optical fluctuation follow the voltage fluctuation. Power spectrum is broad band and continuous peaks at 300Hz and its harmonics due to ps ripples Evolution of attractor is clearly chaotic.

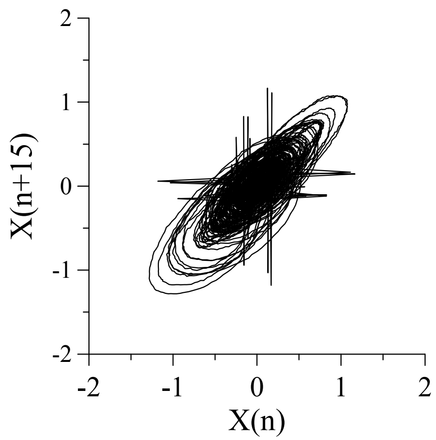


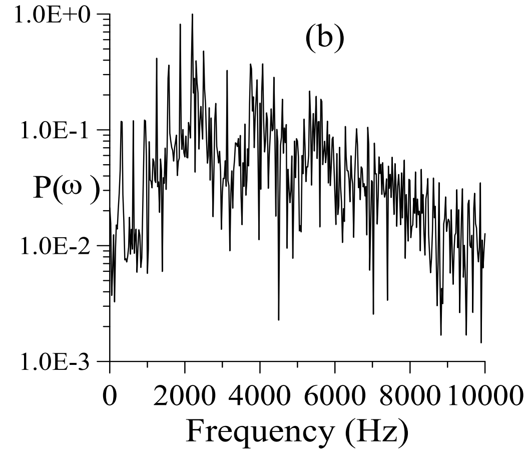
Acoustic Signal

Acoustic signal is proportional to the time derivative of electric power or the time derivative of the voltage fluctuation.
The correspondence is clear

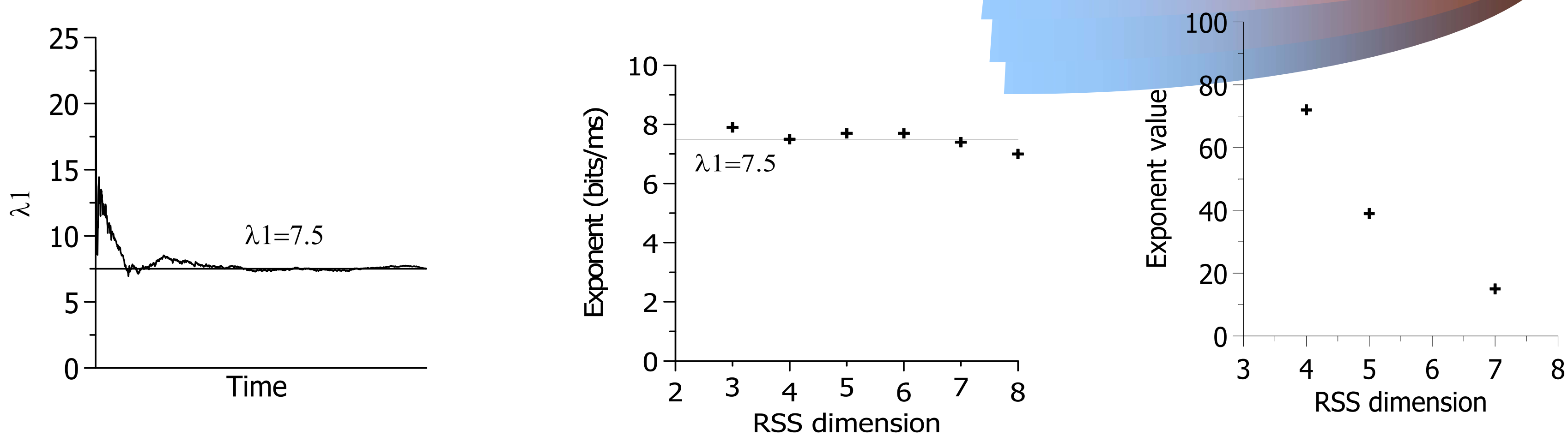






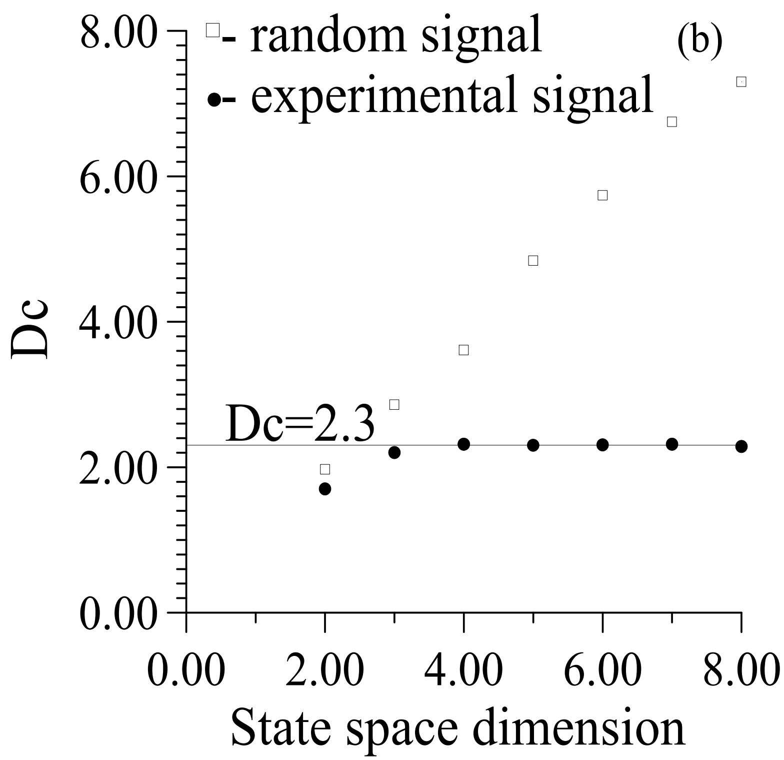


Lyapunov exponent



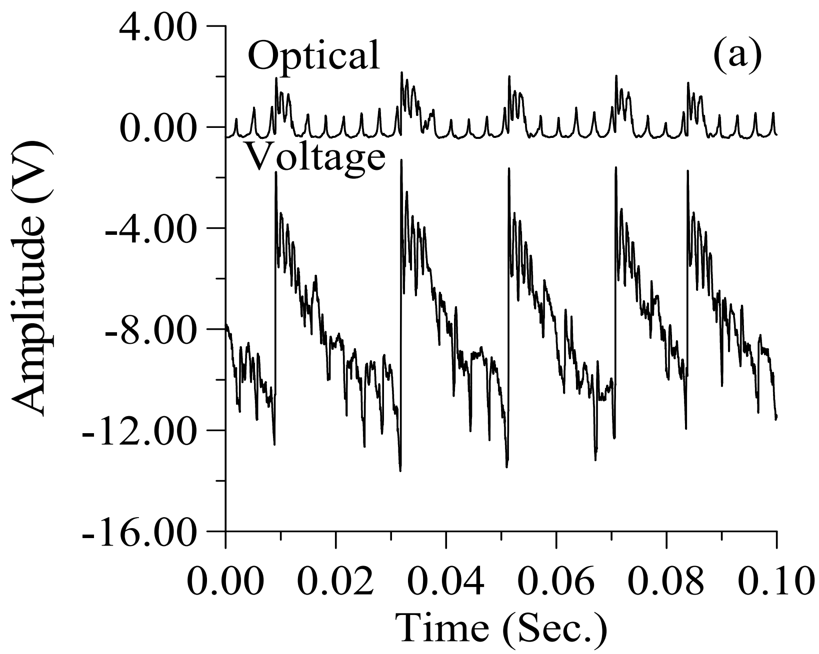
Computation of largest Lyapunov exponent (in bits/ms) for voltage signal. (b) Check of stationarity of computed exponent against dimension of reconstruction state space. (c) Unsteadiness of of exponent for typical random signals

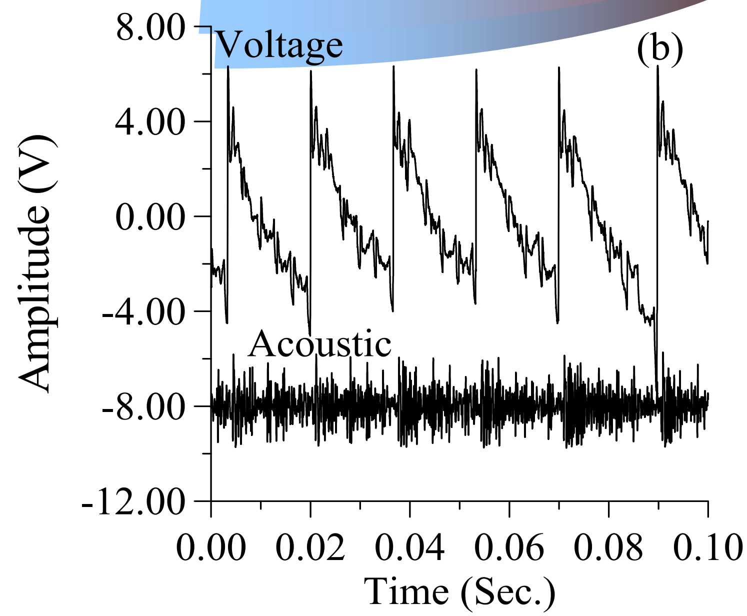
Correlation Dimension



Low, fractal and stationary with increase in state space dimension

Dynamic Similarity amongst signals

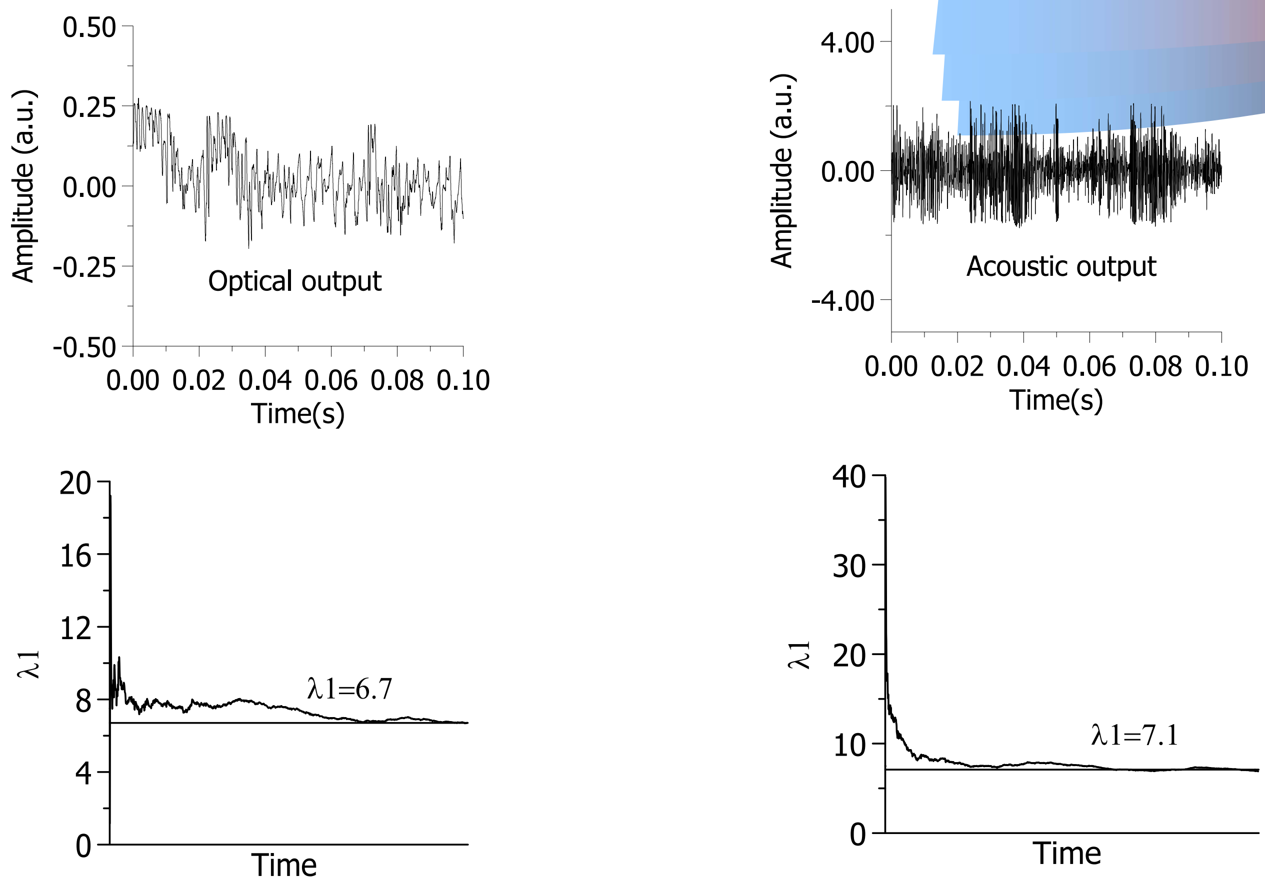




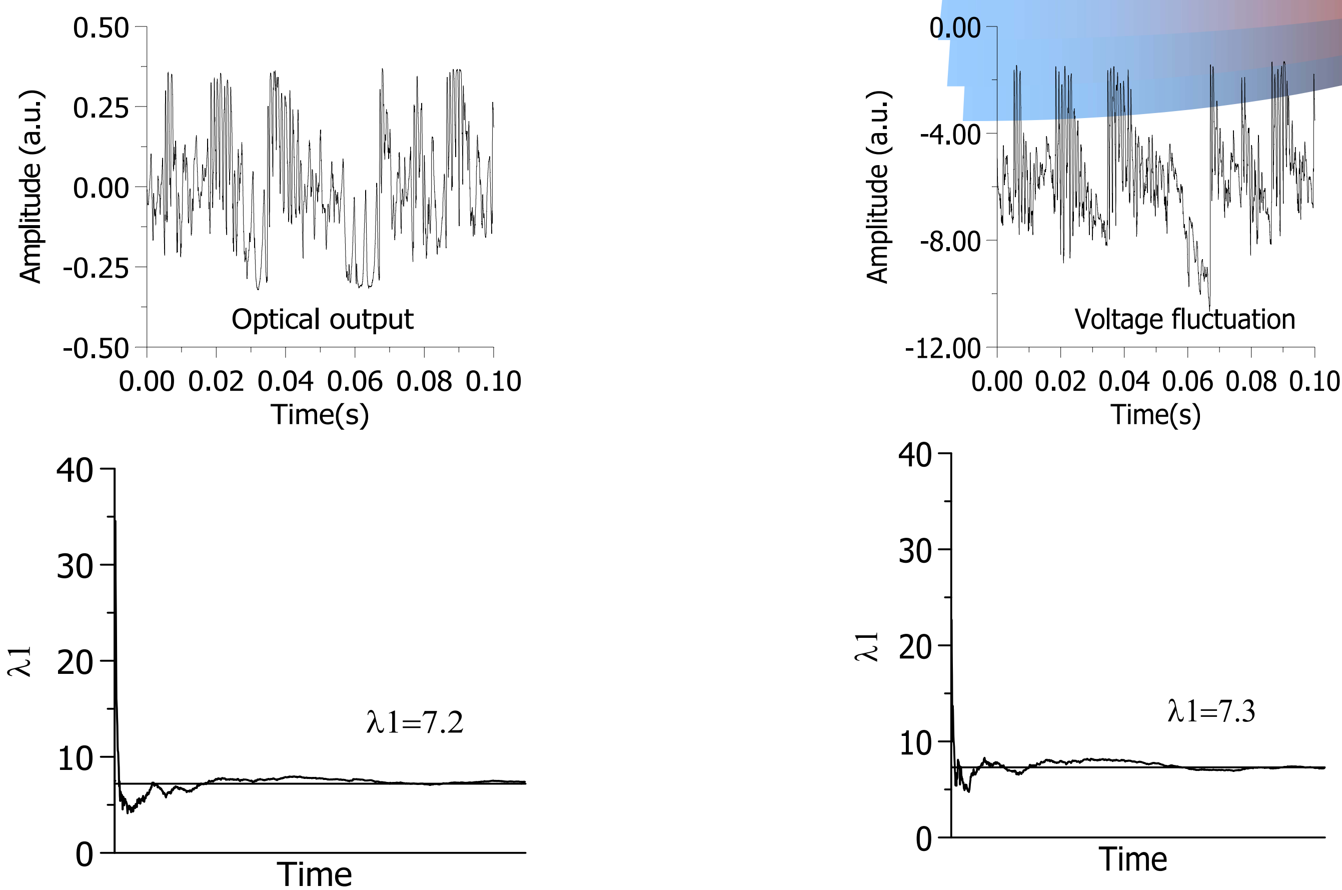
D_c=2.31

D_c=2.32

Dynamic Similarity amongst signals(optical & acoustic)



Dynamic Similarity amongst signals



Summary of post processing of experimental data

- All signals show apparently random real time behavior, continuous power spectra and a typical attractor structure signifying chaos
- Dynamics is controlled by arc current and gas
- All signals have same Liyapunov exponent 7.5 bits/ms
- All signals have same low fractal dimension 2.3
- Though period doubling route is not visible, transition to chaos occurs with arc current and gas flow

A Prescription for monitoring and macro-control

1. Chaos can be controlled

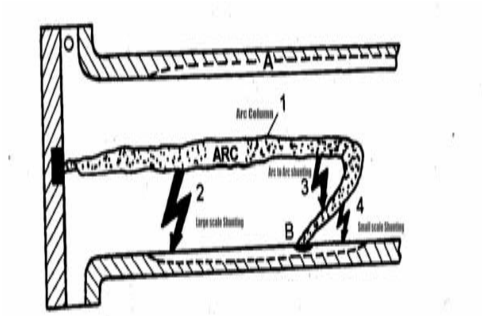
2. Identification of instability control parameters for transition from quasi-periodicity to chaos is to be used to characterize stable conditions

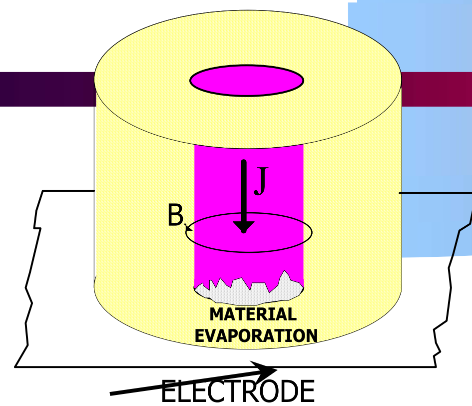
3.Online monitoring of power Spectra, dimensions in phase space, Liyapunov exponent will give an indication of the status of the process and erosion of electrodes (PE King)

4. Feedback control ??-big question

5. Product Database must be compiled & integrated in to the scheme

Generalized theory of arc root instabilities





Cylindrical symmetry near arc root region.

Conservation equation for fluctuating components

Temperature gradient, metal concentration gradient exists in z direction

Bousinesque approximation is valid.

Uniform temperature in r direction for the tiny column considered near arc root.

Current density J_o nearly constant for the cylindrical arc column of radius R.

Basic Equations

$$\frac{\partial v}{\partial t} = -v.\nabla v - \frac{1}{\rho}\nabla p + \nu\nabla^2 v + g\alpha T - g\beta S + \frac{1}{\rho} J \times B$$

$$\frac{\partial T}{\partial t} = -\vec{v}.\nabla T + w\frac{\Delta T}{d} + \kappa\nabla^2 T$$

$$\frac{\partial S}{\partial t} = -\vec{v}.\nabla S + w\frac{\Delta S}{d} + \kappa_S\nabla^2 S$$

$$\frac{\partial B}{\partial t} = \phi(B, v) - \mu_0 J_0 u + \eta_B \nabla^2 B$$

$$\Delta\rho = \rho_0(-\alpha T + \beta S) \qquad \phi(B, v) = (B.\nabla)v + u\frac{B}{r}$$

$$\vec{v} = u\hat{i} + v\hat{j} + w\hat{k} \qquad \kappa = k/\rho s$$

Reduce the equations to non dimensional form

$$\partial_t LY = M_\lambda Y + N(Y)$$

Where Y is plasma field vector,
L is a nonsingular linear operator,
M is a linear operator and
N is a nonlinear operator:

$$Y = \begin{bmatrix} \psi \\ T \\ S \\ B \end{bmatrix} \qquad L = \begin{bmatrix} \nabla^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$M = \begin{bmatrix} \sigma\nabla^4 & -R_l\sigma\partial_r & R_s\sigma\tau\partial_r & -2R^{-1}\sigma\xi Q\partial_z B \\ \partial_r & \nabla^2 & 0 & 0 \\ \partial_r & 0 & \tau\nabla^2 & 0 \\ -2dR^{-1}\partial_z & 0 & 0 & \xi\nabla^2 \end{bmatrix}$$

Rayleigh Number	**R_l**	$$R_l = \frac{g\alpha\Delta T d^3}{\kappa\nu}$$
Solute Raylleigh Number	**R_S**	$$R_S = \frac{g\alpha\Delta S d^3}{\kappa\nu}$$
Prandtl No.	σ	$$\sigma = \frac{\nu}{k}$$
Magnetic Prandtle No.	ξ	$$\xi = \frac{\eta_B}{k}$$
Lewis number	τ	$$\tau = \kappa_S / \kappa$$
Chandrasekhar number	**Q**	$$Q = \frac{B_0^2 d^2}{\mu\rho_0\eta\nu}$$

Modeling Contd.

From detail works by Arneodo, Coullet and Spiegel (ACS),linear version of this type of equation admits solution of the form:

If boundaries are fixed, a solution is

$$Y = Y_{mn} * \Lambda_{mn} e^{st}$$

$$\Lambda_{mn} = \begin{bmatrix} \sin(m.a.r)\sin(n.\pi.z) \\ \cos(m.a.r)\sin(n.\pi.z) \\ \cos(m.a.r)\sin(n.\pi.z) \\ \sin(m.a.r)\cos(n.\pi.z) \end{bmatrix}$$

m & n indicate mode and Y is the four component vector

On Substitution

Modeling Contd

$$M_{mn}(\lambda) = \begin{bmatrix} \sigma q_{mn}^{\ 4} & ma\sigma R_l & -ma\sigma R_S & 2n\pi\xi\sigma QR^{-1} \\ -ma & -q_{mn}^2 & 0 & 0 \\ -ma & 0 & -\tau q_{mn}^2 & \\ -2n\pi dR^{-1} & 0 & 0 & -\xi q_{mn}^2 \end{bmatrix}$$

$$L_{mn}(a) = \begin{bmatrix} -q_{mn}^{\ 2} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$q_{mn}^2 = m^2 a^2 + n^2 \pi^2$$

Characteristic equation $\det\left\|M_{mn} - L_{mn}s\right\| = 0$ corresponding to linear part of the eigen value equation gives the value of 's' in the solution Y. For lowest order instability (m=1,n=1)

$$s^4 + \Pi_3 s^3 + \Pi_2 s^2 + \Pi_1 s + \Pi_0 = 0$$

$$\Pi_0 = q^2 (q^6 - a^2 R_l + a^2 R_S - 4 d \pi^2 R^{-2} Q) \sigma\tau\xi$$

$$\Pi_1 = -a^2 \sigma (\tau + \xi) R_l + a^2 \sigma\tau (1 + \xi) R_S -$$

$$4 d \pi^2 R^{-2} \sigma\xi (1 + \tau) Q + (\sigma\tau + \sigma\xi + \tau\xi + \sigma\tau\xi) q^6$$

$$\Pi_2 = -a^2 \sigma q^{-2} R_l + a^2 \sigma\tau q^{-2} R_S - 4 d \pi^2 R^{-2} \sigma\xi q^{-2} Q +$$

$$(\sigma + \tau + \xi + \sigma\tau + \sigma\xi + \tau\xi) q^4$$

$$\Pi_3 = q^2 (1 + \tau + \sigma + \xi)$$

For marginal stability

$s = i\omega, \qquad \omega \qquad real$

Critical Hyper surface in plasma parameter space

Possible solutions

$$(i) \qquad \Pi_0 = 0 \qquad and \qquad \omega = 0$$

$$(ii) \qquad \omega^2 = \frac{\Pi_1}{\Pi_3} \qquad and \qquad \Pi_1^2 - \Pi_1\Pi_2\Pi_3 + \Pi_0\Pi_3^2 = 0, assumed \qquad \Pi_1 \geq 0$$

Both conditions define a critical hyper surface

By substitution an amplitude equation in plasma parameter space near the critical hypersurface Can be defined

Solution Strategy

1. The set of partial differential equations for the near arc root region support infinite number of normal modes
2. Eigen values of the Jacobian matrix show that except for the fundamental mode and the modes near it, all the rest have negative real part and get damped
3. Among the four eigen values offered by the characteristic equation one is real negative
4. At criticality, Three eigenvectors corresponding to remaining three eigen values span the null space of the Jacobian matrix

Solution Strategy

5. The real negative solution results in stable solution, can be ignored and a cubic polynomial for roots is obtained

6. The complete solution will be a superposition of stable and unstable modes

7, The Amplitude equation in the three vector is written as a third order differential equation in near critical region

8. The final third order nonlinear amplitude equation describes temporal evolution of the plasma field vector for marginal stability.

The linear and cubic nonlinear amplitude equation

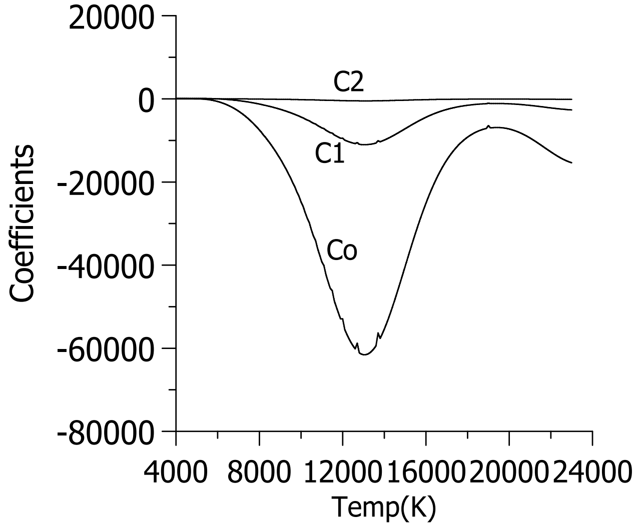
$$\dddot{A} + C_2\ddot{A} + C_1\dot{A} + C_0 A = 0$$

$$C_0 = \frac{\Pi_o}{\Pi_3}, C_1 = \frac{\Pi_1}{\Pi_3} - \frac{\Pi_0}{\Pi_3^2} \, and C_2 = \frac{\Pi_2}{\Pi_3} - \frac{\Pi_1}{\Pi_3^2} + \frac{\Pi_0}{\Pi_3^3}$$

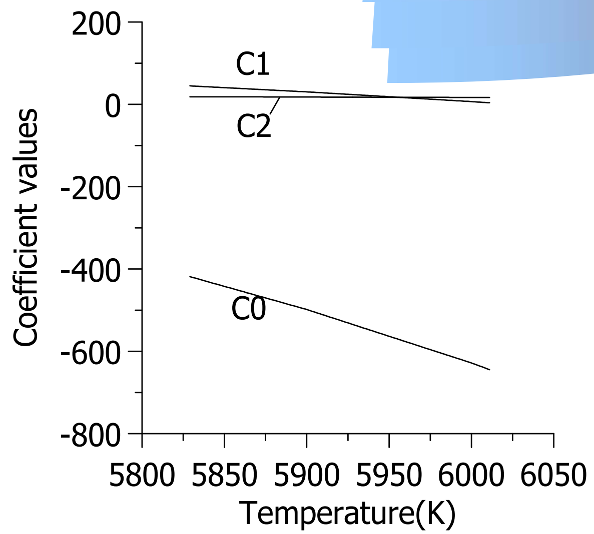
$$\dddot{A} + C_2\ddot{A} + C_1\dot{A} + C_0 A = \zeta(A)$$

$$\dddot{A} + C_2\ddot{A} + C_1\dot{A} + C_0 A = C_4 A^3$$

Coefficients near criticality (Argon)



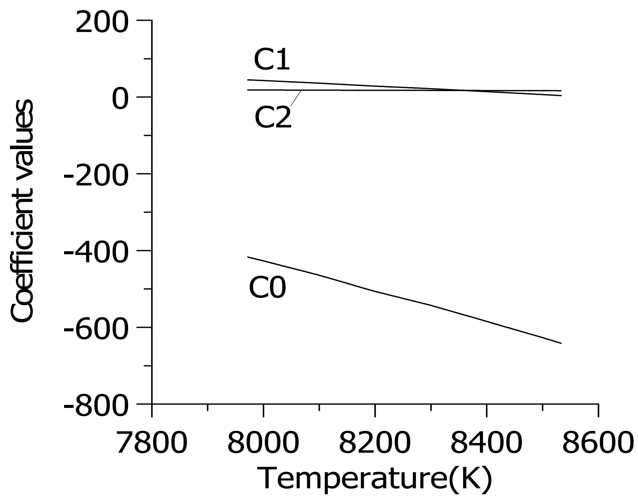
I=400A



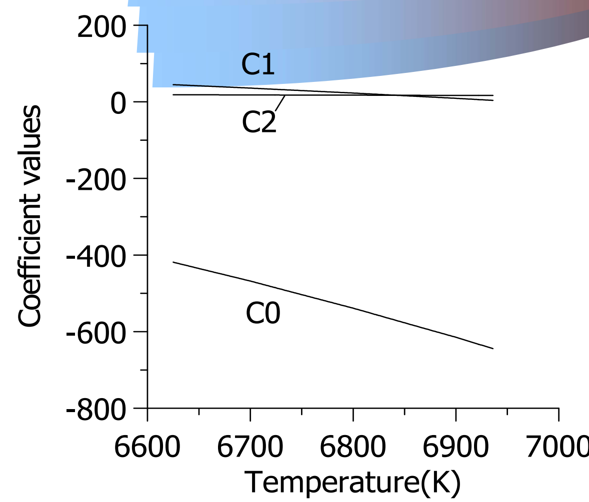
I = 400A

Expanded Scale

Coefficients near criticality(Argon)

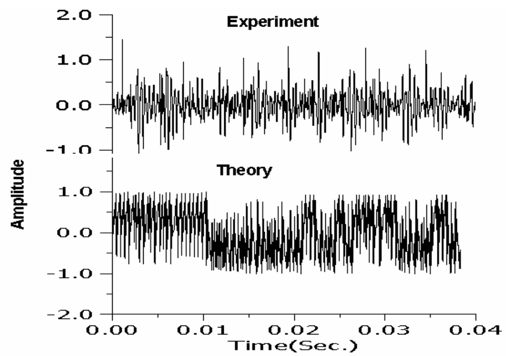


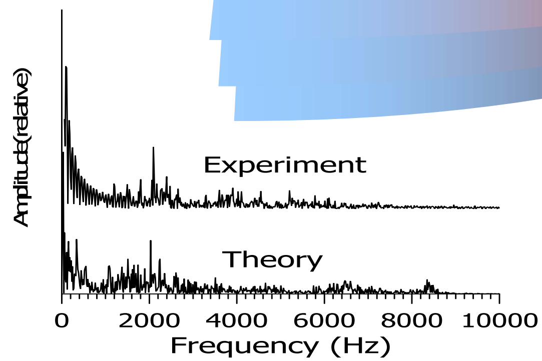
I = 100A

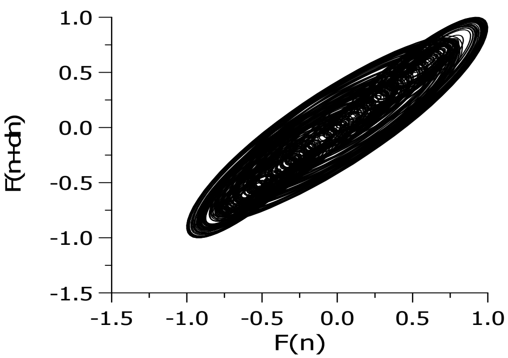


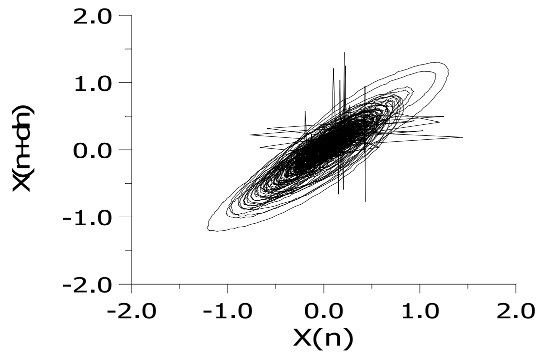
I = 200 A

Comparison with experiments

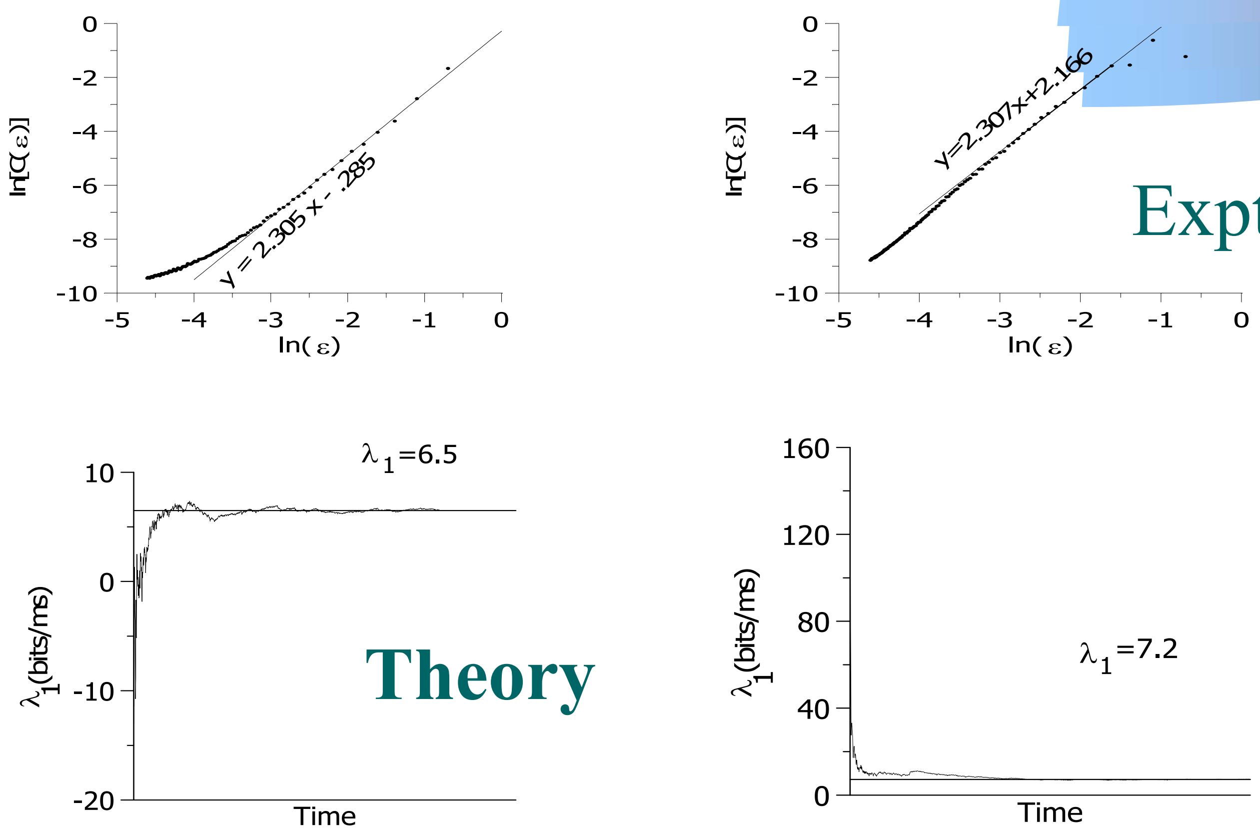






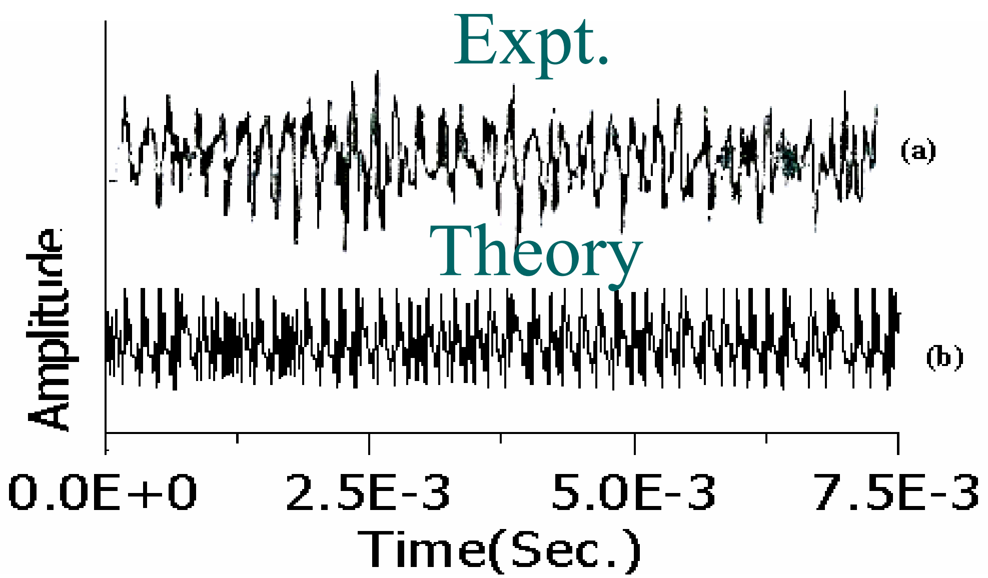


Comparison with experiments



Comparison with Experiments Performed by

Brilhac, Pateyron, Coudert,Fauchais and Bouvier
[“Study of dynamic and static behavior of dc vortex plasma torches: Part: II well-type cathode”, Plasma Chem. Plasma Process., 15, 257-277, 1995.]



Acoustic Signal

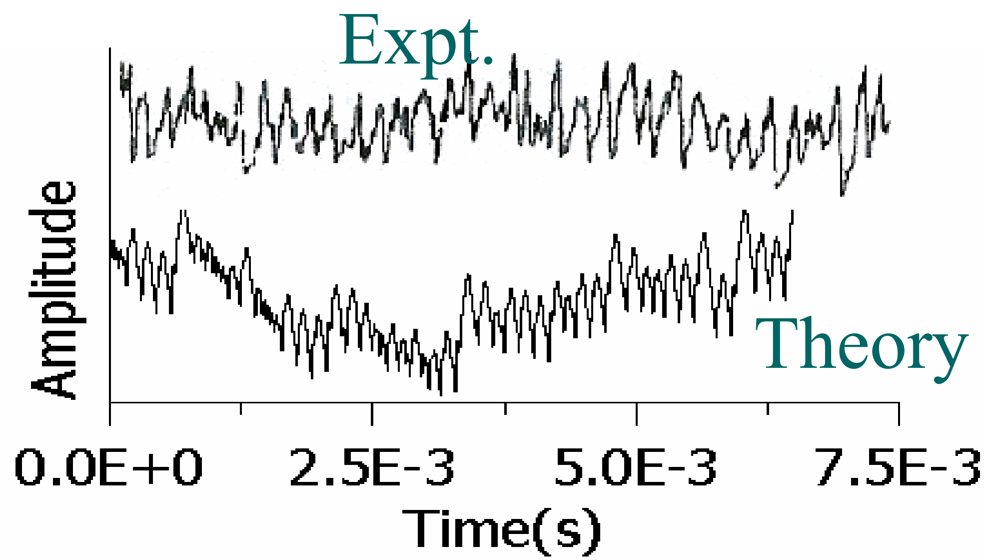
C_0=-140

C_1=50

C_2=1

G=1.44e-4

Brilhac, Pateyron, Coudert, Fauchais and Bouvier
[“Study of dynamic and static behavior of dc vortex plasma torches: Part: II well-type cathode”, Plasma Chem. Plasma Process., 15, 257-277, 1995.]



Voltage Signal:

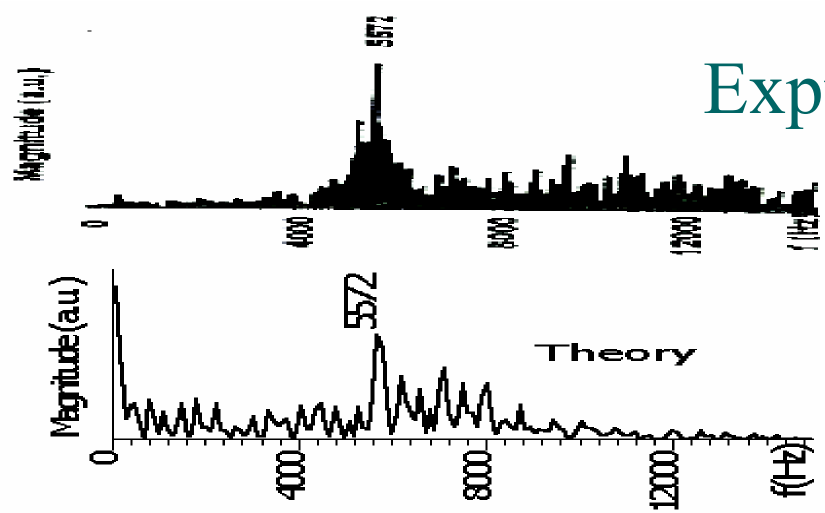
C_0=-140

C_1=50

C_2=1

G=1.44e-4

Brilhac, Pateyron, Coudert,Fauchais and Bouvier
[“Study of dynamic and static behavior of dc vortex plasma torches: Part: II well-type cathode”, Plasma Chem. Plasma Process., 15, 257-277, 1995.]



Expt.

Power Spectra for acoustic signals

C_0=-140

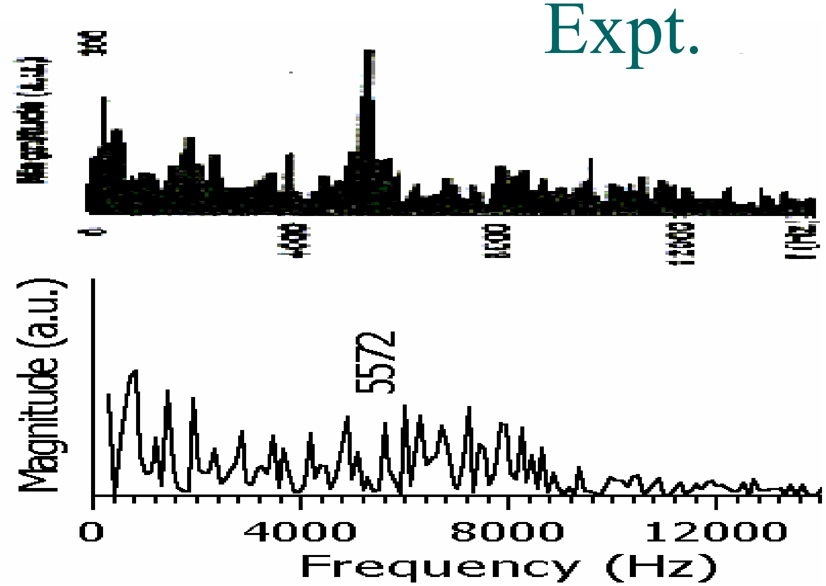
C_1=50

C_2=1

G=1.44e-4

Brilhac, Pateyron, Coudert,Fauchais and Bouvier
[“Study of dynamic and static behavior of dc vortex plasma torches: Part: II well-type cathode”, Plasma Chem. Plasma Process., 15, 257-277, 1995.]

Expt.



Power spectra for voltage signals

C_0=-140

C_1=50

C_2=1

G=1.44e-4

Control on arc stability through chaos control

1. **Basis : Chaotic dynamics is controllable.**

Currently, this can be predicted in arcjet plasmas

and hence controlled

2. **Macro control through manipulation of the input operating parameters i.e. gas flow pattern, current, secondary gas injection, temperature near arc root etc.**

3. **Micro control through confining the dynamics of the plasma jet to a selected narrow region of the phase space. Stabilize the system dynamics to a high period orbit through application of computed parameter perturbation.**

OTT-GREBOGI-YORK METHOD FOR CONTROLLING CHAOS [1990]

A chaotic attractor is comprised of a set of infinite number of unstable periodic orbits.

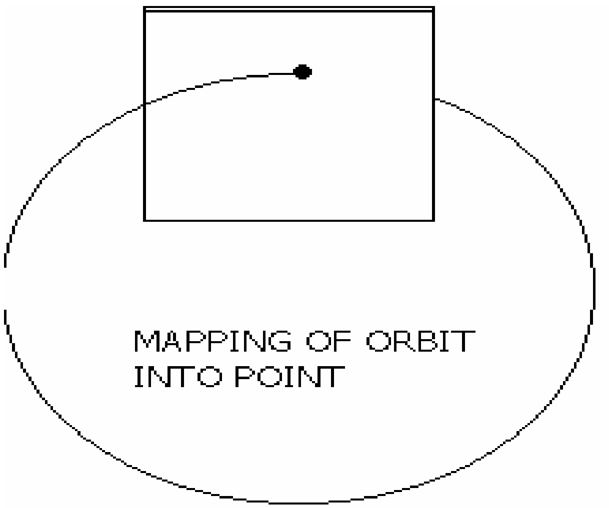
ii) A small time dependent perturbation in control parameter can be provided when the system is passing through a small window in phase space

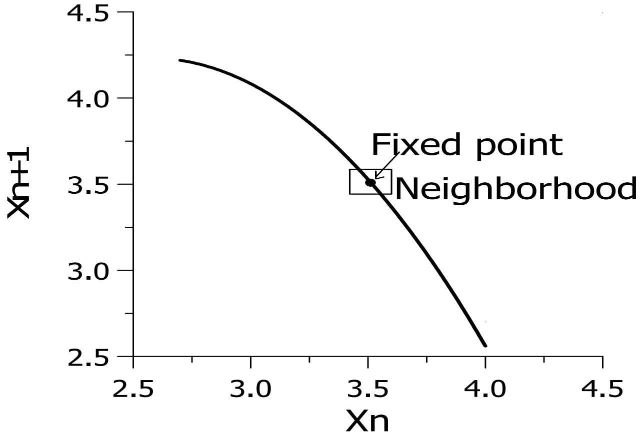
iii) The perturbation is to be designed to drive the system towards the selected high period orbit. This is called stabilizing the orbit

iv) The same system can be made to behave in variety of manners just by stabilizing different orbits through proper design of the perturbation.

(v) For a plasma processing system the perturbation can be voltage, current pulse generated from the three fluctuating signals, tailored and used as feedback.

Mapping orbits to a neighbourhood in Poincarre Section





OGY METHOD FOR CONTROLLING CHAOS
Current Status

Successfully applied to simpler systems

Vibrating magnetoelastic Ribbon [1990]

Suppression of chaotic flow in thermal convection loop [1991]

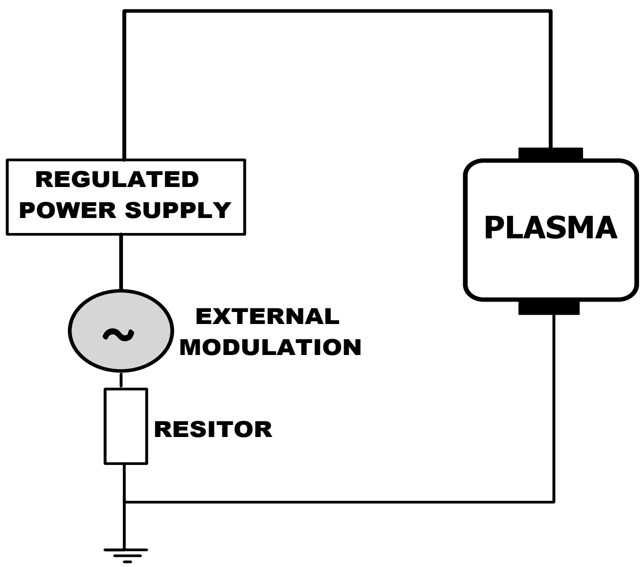
Stabilizing high period orbits in diode resonator[1992]

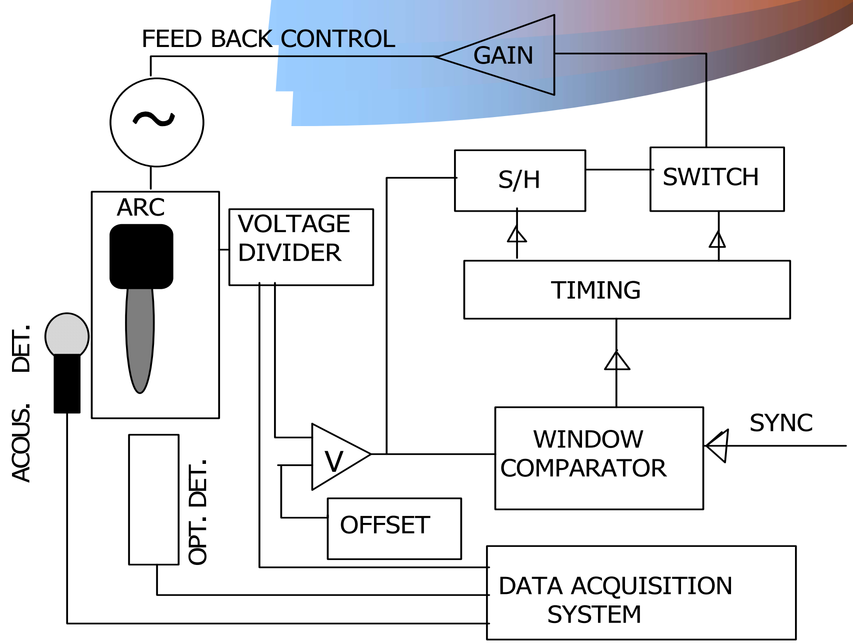
Low pressure discharge plasma through voltage perturbation [1994]

Stabilization of unstable low periodic orbits in plasma diode [2000]

Arcjet plasma is a more complex system and a thorough study is needed to determine exact perturbation

- *A conceptual Scheme for Applying OTT-GREBOGI-YORK*
- *METHOD FOR CONTROLLING Dynamics of Arc plasma jets*





Application of OGY method in Plasma devices

Possible modified OGY scheme for application in spray plasma torches

SUMMARY

1. The paper has focused only on the jet stability and electrode erosion issues associated with achieving feedback control of plasma spray systems
2. It has been experimentally established that atmospheric arc plasmas operate in intermittent chaos primarily controlled by current and plasma gas
3. A generalized theory of such instabilities has been developed that can predict dynamics of arc root
4. The results have been validated against experimental data
5. The chaos transition depends on electrode material, arc current, near wall temperature and its gradient.
6. Two prescriptions for control has been prescribed. Firstly the desired operating regime can be predicted through the generalized theory. Secondly OGY technique can be applied to push the system in to the desired region of phase space.

THANK YOU!!!