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# DISCOVERIES OF WAVES IN DUSTY PLASMAS: AN OVERVIEW

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**SAVAR, DHAKA, BANGLADESH**

# ▪ 60th Birthday: Professor Padma Shukla:

who is one of the pioneers:

- Dusty Plasma Physics
- Waves in Dusty Plasmas
- Nonlinear Phenomena in Dusty Plasmas

Not only this, Prrof. Shukla has mentored, and is still mentoring the most of the young plasma scientists from different parts of the globe. I am one of them (since 1995). There are many things to learn from him, e. g.

- How to respect a senior
- How to love a young
- How to guide and inspire a young

**We always find Professor Padma Shukla with smiling face at his office. To honor him as distinguished international professor: RUB International Chair and Director International Centre for Advanced Studies in Physical Sciences (ICASPS).**

Prof. Padma Shuka is not only a big source of new ideas in modern plasma physics, but also a big source of inspiration for all of us

to go ahead further and further ------------

On the behalf of his all students, and his all young collaborators as well as all the participants from the different parts of the globe:

I wish

an ever-green, long & cherished life

of

**Professor Padma Shukla**

# OUTLINE

- Introduction
  - Dusty Plasma
  - Parameters
  - Research Areas
- Discoveries

  Theory with

  Experiment
- SUMMARY

# ❑ Introduction

➢ **Dusty Plasma?**

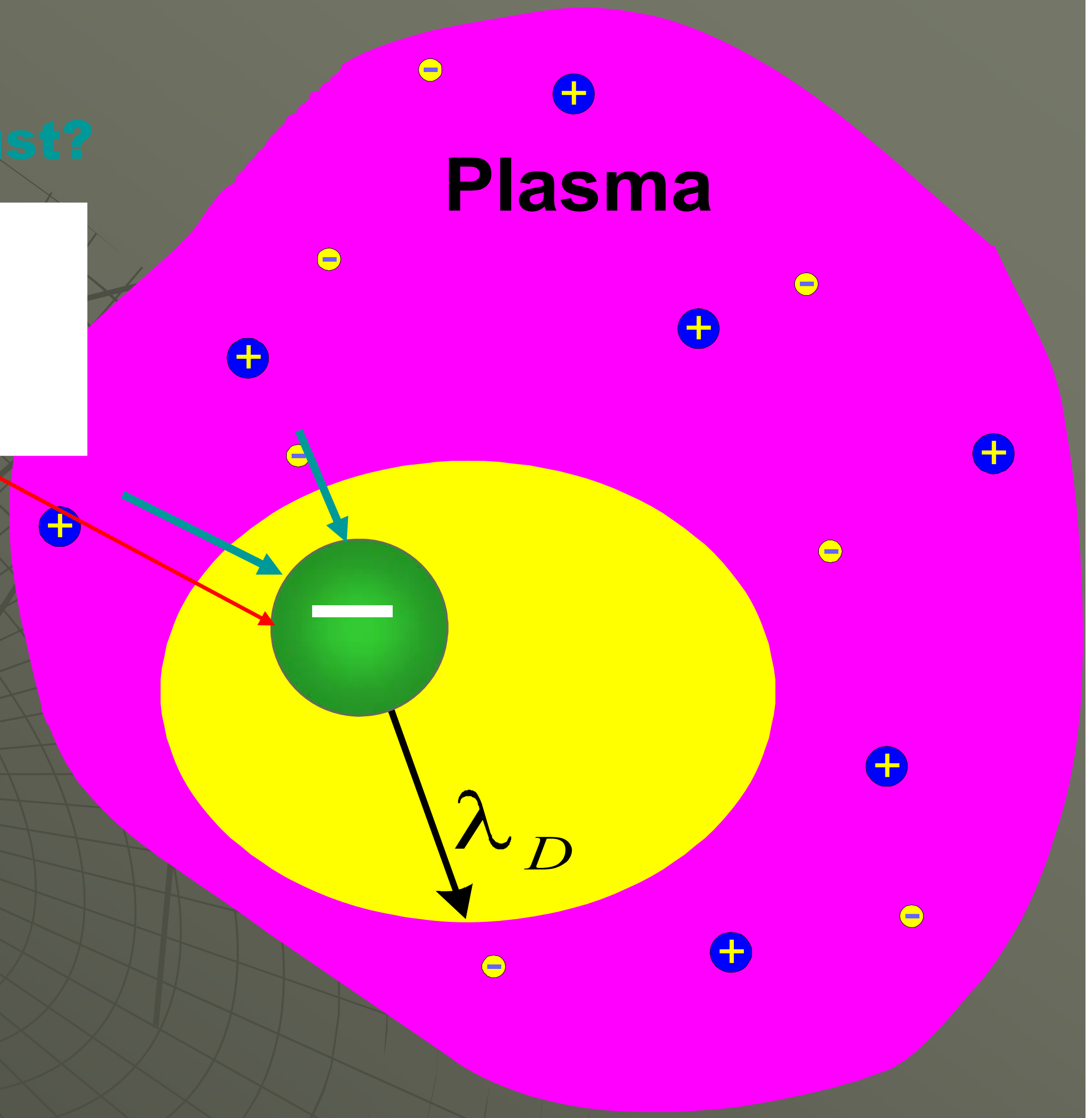
**Can we/plasma avoid dust?**

**Dusty Plasma:**
plasma + **dust (small particles of solid)**

- absorbs electrons and ions

- becomes negatively charged in this case

- is finally shielded by other electrons and ions ($\lambda_D$)



- The ranges of size, mass & charge of dust are very wide:
  - size: from μm to mm: not constant in general.
  - mass: from millions to billions times heavier than ions:

    but not constant in general.
  - charge: not neutral: + or – : depending on charging proc.:

    $10\text{-}10^4$ e (-e) charge: not constant in general.
- Complex Plasma : The addition of dust having variable size, variable mass and variable charge makes a plasma system very complex, and arises an unsolvable complexity. This is why, a dusty plasma is also termed as a Complex Plasma.
- Dirty Plasma : It is also known as Dirty Plasma?

Ref: review articles: Geortz (1989); Mendis & Rosenberg (1994)

books: Verheest (2000); Shukla and Mamun (2002)

## ➢ Plasma Parameters

- Typical parameters of dust-laden plasmas in interstellar clouds, zodiacal dust disc and Haley's comet

| Character-istics | interstellar clouds | zodiacal dust disc | Haley's comet |
|---|---|---|---|
| $n_e$ ($cm^{-3}$) | $10^{-4}$ – $10^{-3}$ | 1 – 10 | $10^{2}$ – $10^{4}$ |
| $T_e$ (K) | 10 – 20 | $10^{4}$ – $10^{5}$ | $10^{3}$ – $10^{4}$ |
| $n_d$ ($cm^{-3}$) | $10^{-7}$ – $10^{-6}$ | $10^{-12}$ – $10^{-11}$ | $10^{-8}$ – $10^{-3}$ |
| $r_d$ (μm) | 0.1 – 0.5 | 1 – 10 | 0.1 – 10 |

- Typical parameters of dust-laden plasmas in Saturn's rings

| Characteristics | E-ring | F-ring | Spokes |
|---|---|---|---|
| $n_e$ ($cm^{-3}$) | 10 – 20 | 10 – 20 | 0.1 – $10^2$ |
| $T_e$ (K) | $10^5$ – $10^6$ | $10^5$ – $10^6$ | $10^4$ – $10^5$ |
| $n_d$ ($cm^{-3}$) | $10^{-7}$ – $10^{-6}$ | 1 – 10 | 1-3 |
| $r_d$ (μm) | 0.5 – 1.5 | 0.5 –1. 5 | 0.5 –1. 5 |

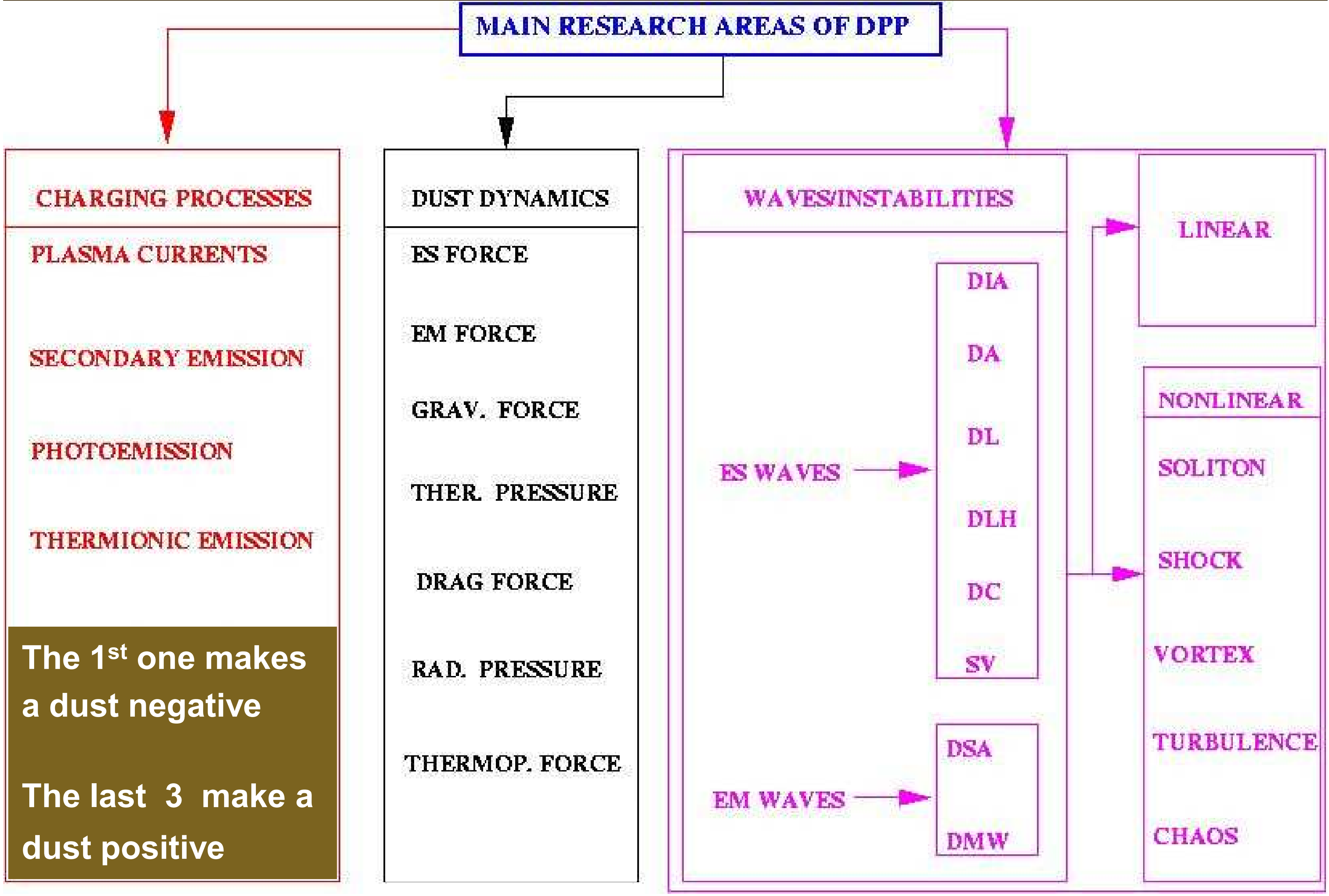
- Typical parameters of dust-laden plasmas in NLCs, rocket exhausts and flames

| characteristics | NLCs | rocket exhausts | flames |
|---|---|---|---|
| $n_e$ ($cm^{-3}$) | $10^3 – 10^4$ | $10^{12} – 10^{13}$ | $10^{11} – 10^{12}$ |
| $T_e$ (K) | 100 – 200 | $10^3 – 10^4$ | $10^3 – 10^4$ |
| $n_d$ ($cm^{-3}$) | $10 – 10^2$ | $10^7 – 10^8$ | $10^{10} – 10^{11}$ |
| $r_d$ (μm) | 0.1 – 1 | 0.1 –1 | 0.01 –0.1 |

- Typical parameters of dust-laden plasmas in laboratory devices

| characteristics | Q-machine (DPD) | dc discharges | rf discharges |
|---|---|---|---|
| $n_e$ ($cm^{-3}$) | $10^6 – 10^7$ | $10^9 – 10^{10}$ | $10^9 – 10^{10}$ |
| $T_e$ (K) | $10^3 – 10^4$ | $10^4 – 10^5$ | $10^4 – 10^5$ |
| $n_d$ ($cm^{-3}$) | $10^3 – 10^4$ | $10^3 – 10^4$ | $10^5 – 10^6$ |
| $r_d$ (μm) | 10 – 20 ($Al_20_3$) | 1 – 5 (Al)<br>60–65 (glass) | 5 – 10 ($Si0_2$) |
| $Z_d$ | $10^3 – 10^4$ | $10^5 – 10^6$ | $10^3 – 10^4$ |

# ➢ Main Research Areas: Multidisciplinary Subject



## ❑ Discoveries:
## Theory with Experiment:

- A theoretician must keep in mind: a correct & realistic theory must comply with any of the following three:
  - ✓ interprets natural events (beauty of nature?).
  - ✓ agrees with any experiment performed already.
  - ✓ proposes experiment to be performed in future.

Theory and experiments in dusty plasma physics have no any exception. There are many theories and experiments on dusty plasma physics (carried out during last two decades) which supports each other. We now discuss on some of the theories and experiments on waves in dusty plasma:

## DIA Waves:

$$\frac{\omega}{k} = \sqrt{\left(\frac{n_{i0}}{n_{e0}}\right)\left(\frac{T_e}{m_i}\right)}$$

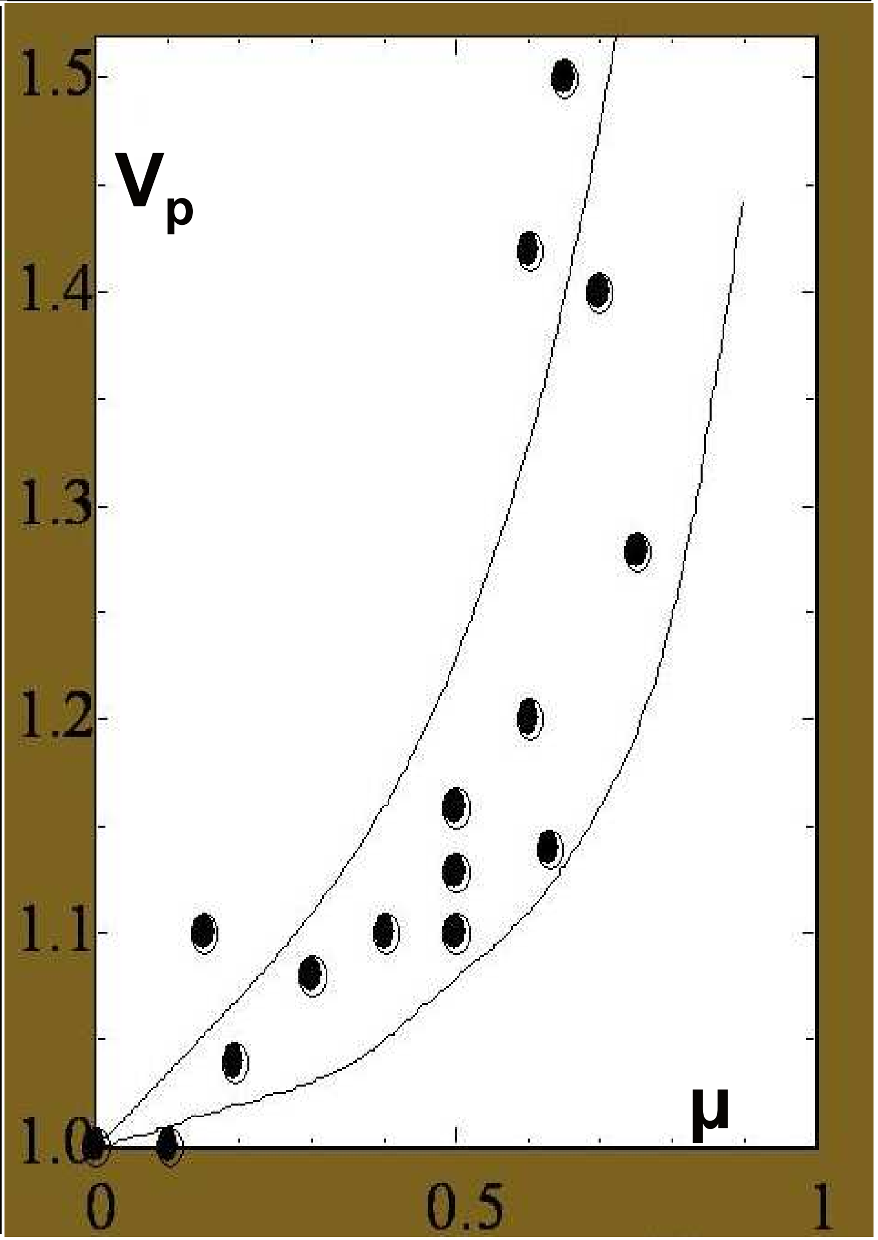
- Theory: Shukla and Silin (1992)

  Experiment: Barkan et al. (1996).

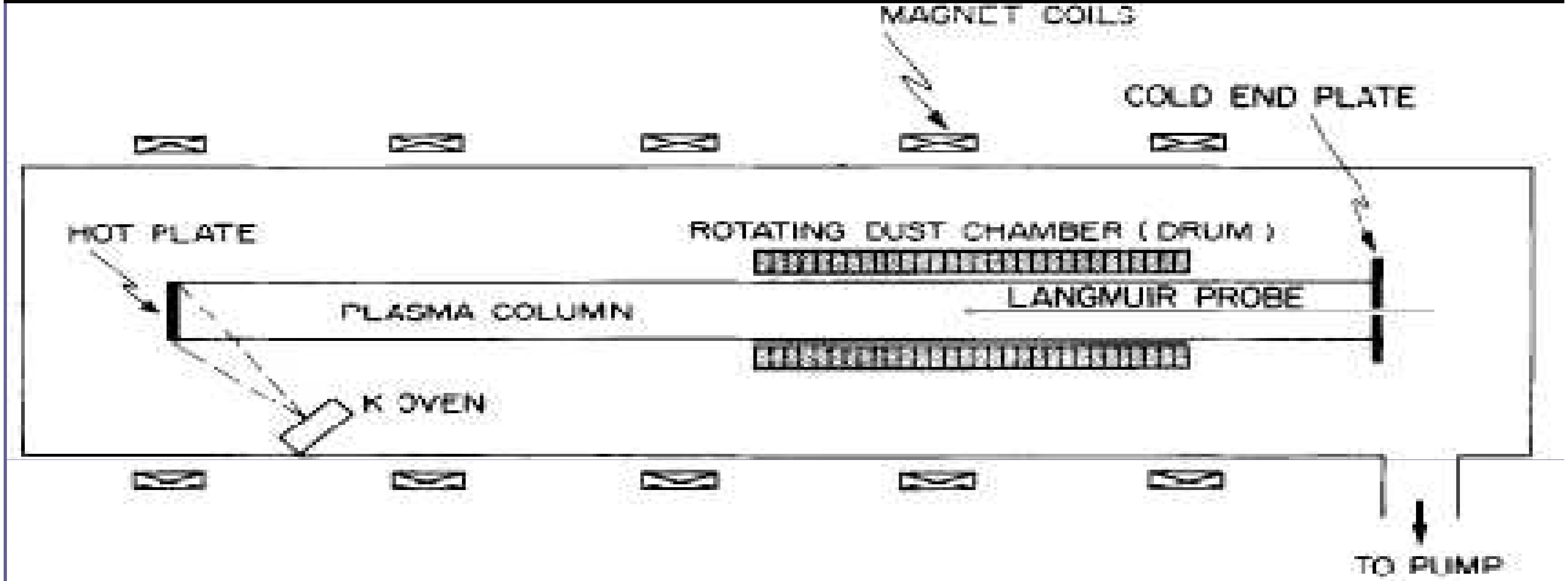
- $n_{i0}/n_{e0}=1+\mu$, where $\mu=Z_d n_{d0}/n_{e0}$. This significantly increase the phase speed, but decrease the Landau damping.

- IA waves are subject to ion Landau damping, which is severe for $T_e \sim T_i$. But, this is not the case for DIA waves, where wave-particle resonance at $V_{Ti} \sim V_P$ no longer holds with $V_P >> V_{Ti}$.

- Ion-temperature effect should be taken into account.



# Experimental Setup & Parameters: DIWs [Barkan et al. (1995)]:




Parameters:

$n_p \sim 10^5 - 10^9$ cm$^{-3}$

$T_e \sim 0.2$ eV

$T_i \sim 0.2$ eV

$r_d \sim 0.5 - 7.5$ μm

The K+ plasma column of a Q-machine is surrounded over it end portion (30 cm) by a rotating dust dispenser that continuously recycles hydrated aluminum silicate (kaolin) dust through the plasma.

The main plasma diagnostics are performed by means of Langmuir probe that also determines how negative charge in the plasma is devided between free electrons and dust.

## ▪ DA Waves:

$$\frac{\omega}{k} \approx \sqrt{\left(\frac{Z_d n_{d0}}{n_{i0}}\right)\left(\frac{Z_d T_i}{m_d}\right)}$$

- Theory:

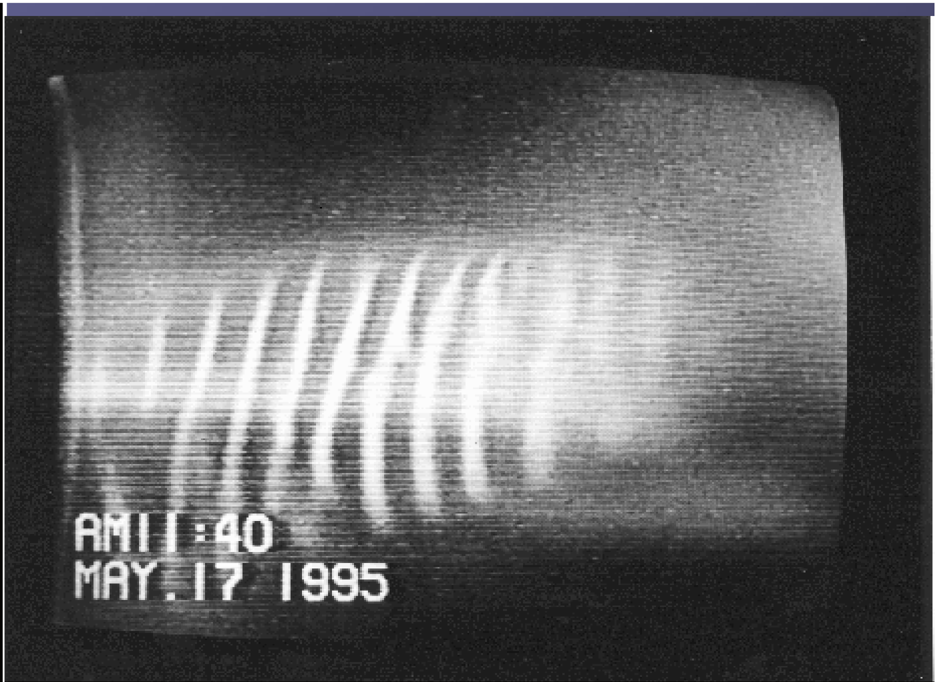
  Shukla: Capri Meeting (1989)

  Rao, Shukla and Yu: PSS (1990)

  Experiment:

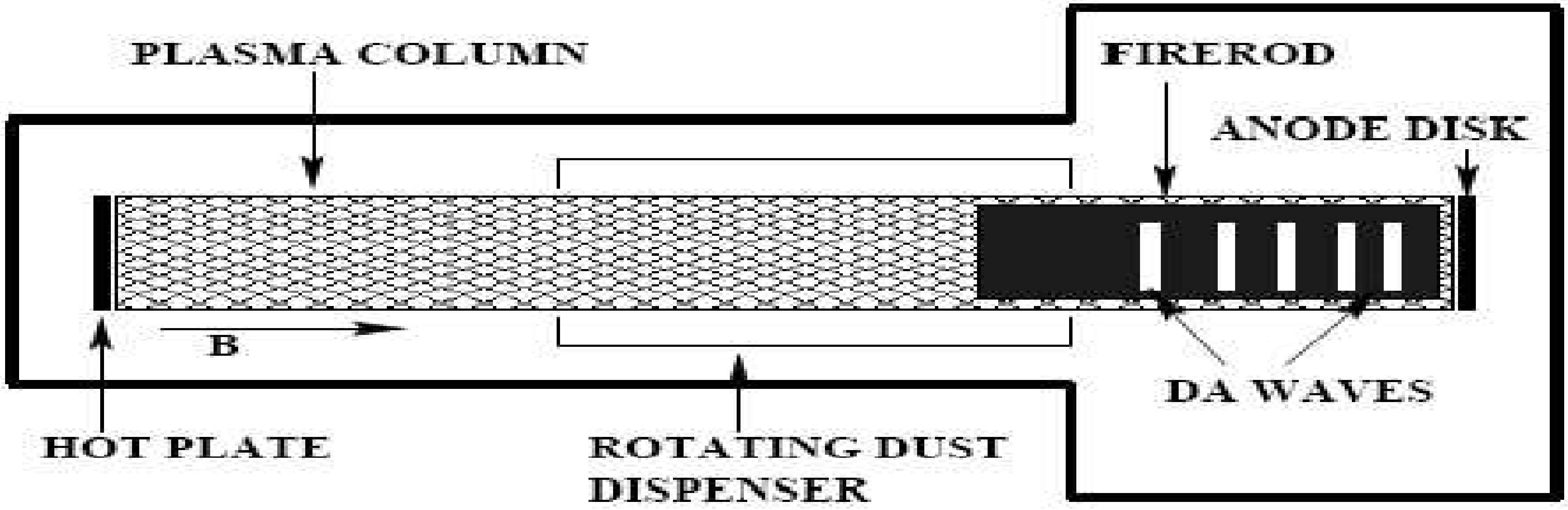
  Barkan et al (1995).

- The restoring force mainly comes from elelectron and ion thermal pressures and the inertia is provided by the dust mass.
- This mode is due to the dynamics of dust.




- DA is very low frequency mode (V~9 cm/s, λ~0.6 cm, f~15 Hz).
- DA waves are visible with naked eyes.
- This novel mode exists in both space and laboratory dusty plasma

# • Experimental Setup & Parameters: DAWs [Barkan et al. (1995)]:




**Parameters**:

$n_p \sim 10^8 - 10^9$ cm-3

$T_e \sim 2 - 3$ eV

$T_i \sim 0.025$ eV

$r_d \sim$ 1-7 micron (kaolin dust)

$Z_d \sim 10^3$

$n_d \sim 10^5$ cm$^{-3}$

The K+ plasma column of a Q-machine is surrounded over it end portion (30 cm) by a rotating dust dispenser that continuously recycles hydrated aluminum silicate (kaolin) dust through the plasma.

A fire-rod is produced within this plasma column by biasing the anode disk at +200 V.

Negatively charged dust are trapped within the fire-rod, where DA waves are observed.

## ▪ DIA Shock Waves:

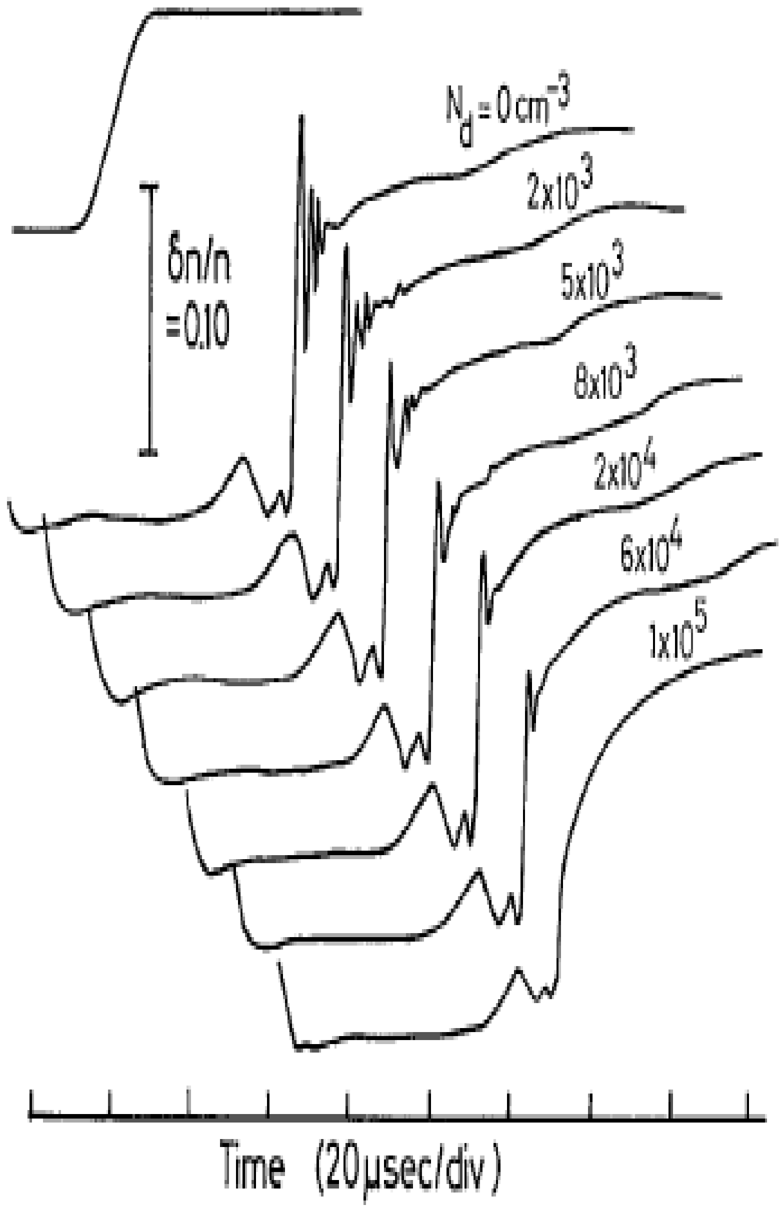
- Theory:

  Nakamura, Bailong & Shukla (1999)

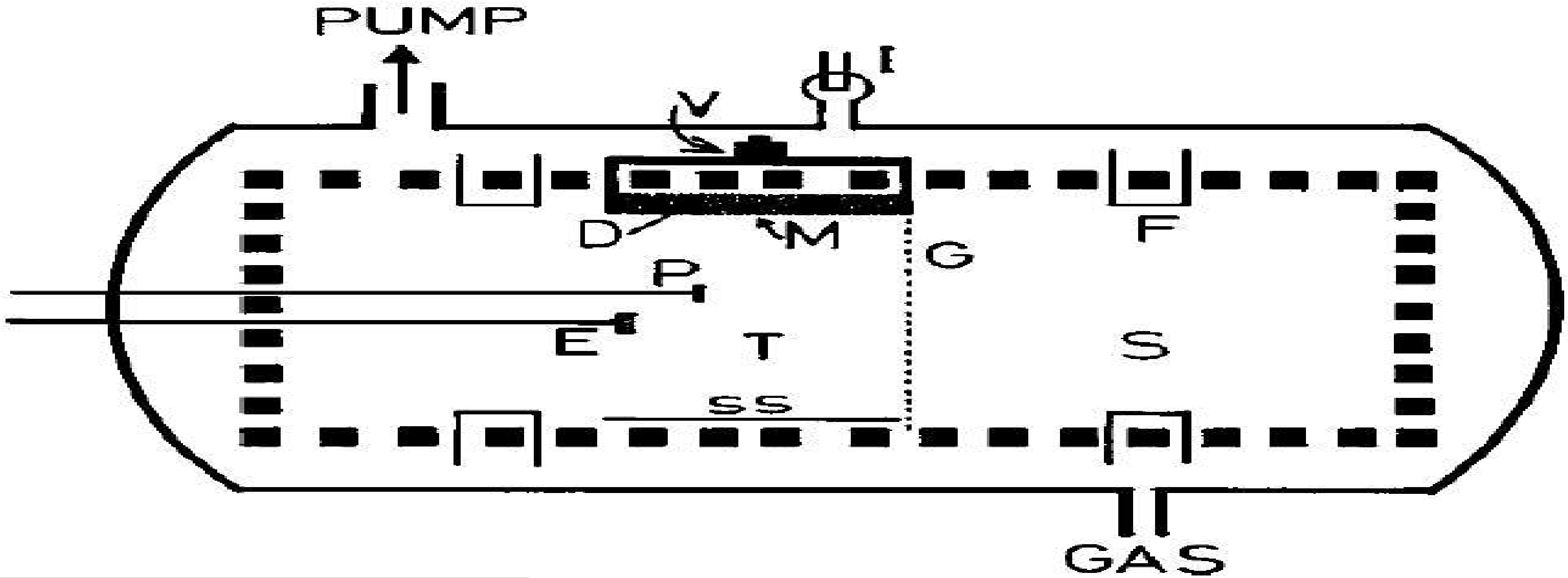
- Experiment:

  Nakamura, Bailong & Shukla (1999)

  - The number of oscillatory wave structures behind the shock is maximum when no dust is present.
  - It decreases with the increase of dust number density.
  - The sufficient high dust number density leads to laminar (monotonic) shock front.



- Experimental Setup & Parameters: DISSs [Nakamura et al (1999)]




- **Parameters**:

  $n_e \sim 10^8 – 10^9$ cm$^{-3}$

  $T_e \sim (1– 1.5)\times10^4$ K

  $T_i \sim 0.1\ T_e$

  $r_d \sim 4$ μm (glass)

  $Z_d \sim 10^5$ for $n_d<10^3$ cm$^{-3}$

  $Z_d \sim 10^2$ for $n_d \sim 10^5$ cm$^{-3}$

DDP device [40cm x 90 cm] is separated into source and target section by mesh grid (electrically floating). It is evacuated down to $5\times10^{-7}$ torr by a turbo-molecular pump. Ar gas was bled into the chamber at a partial pressure ($5\times10^{-4}$ torr).

A dust dispenser fitted at its target section consists of a dust reservoir coupled to an ultrasonic vibrator which is tuned at 27 kHz to vibrate the dust reservoir.

# ▪ DA Solitary Waves:

- Theory:

  Roa, Yu & Shukla (1990)

  [small aplitude DASWs: RPM]

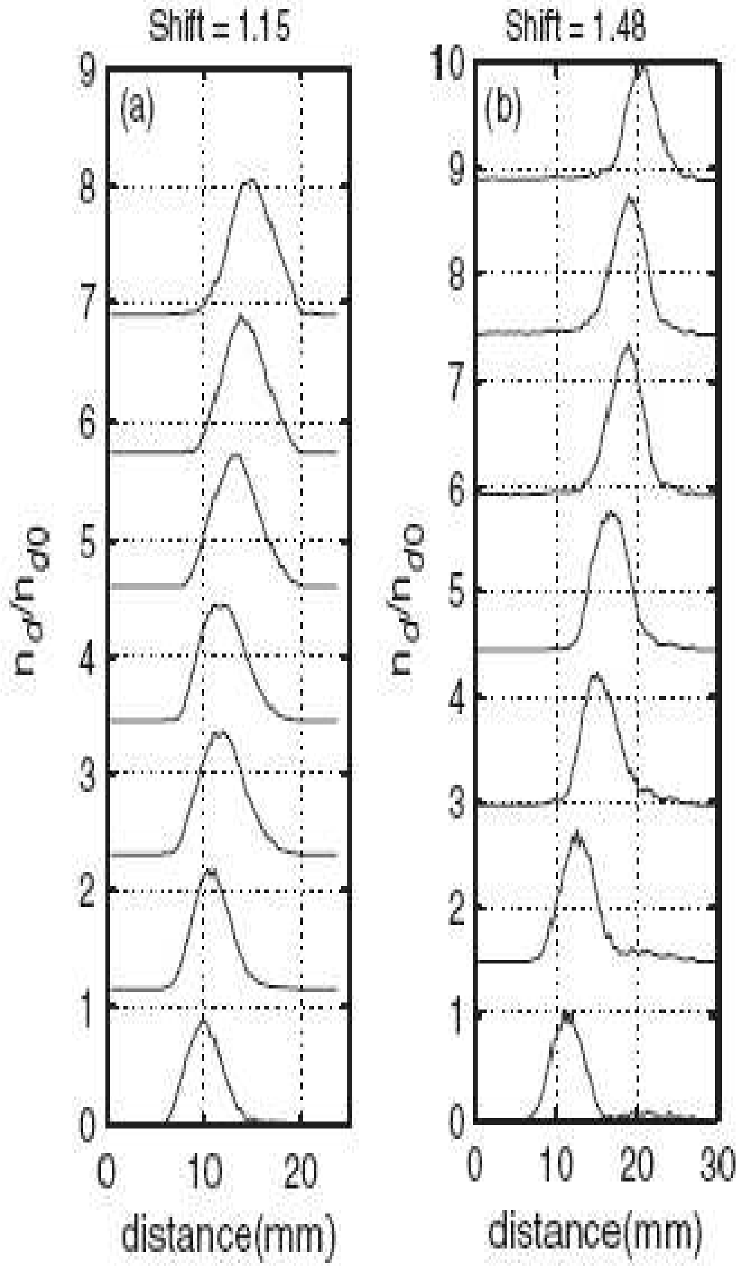
  Mamun, Cairns & Shukla (1996)

  [arbitrary amplitude DASWs: PPM]

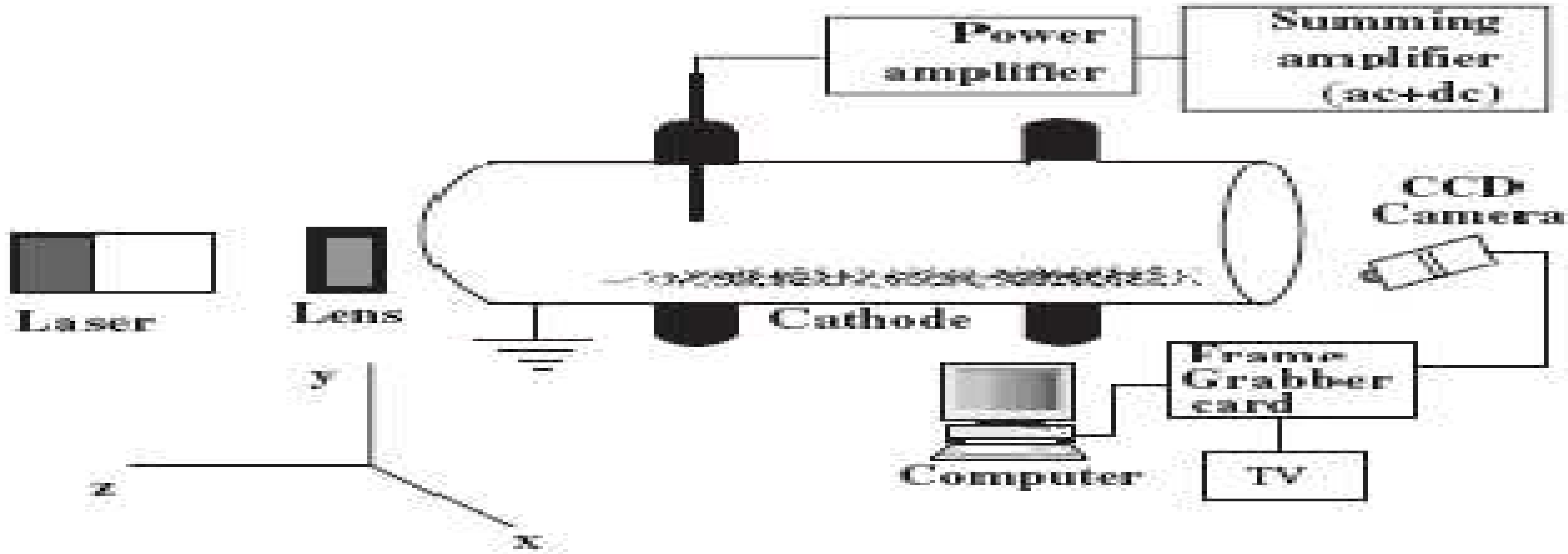
- Experiment:

  Bandyopadhyay et al. (2008)

  - DASWs at two different excited pulse voltage for (a) 60V and (b) 120V.
  - The amplitude and speed (width) increases (decreases) with the increase of applied voltage.



- Experimental Setup & Parameters: DASWs [Bandyopadhyay et al. (2008)]




**Parameters**:

$n_i \sim 7 \times 10^7$ $cm^{-3}$

$T_e \sim 8$ eV

$T_i \sim 0.3$ eV

$r_d \sim 0.5$ μm

$m_d \sim 10^{-13}$ kg

$Z_d \sim 3 \times 10^3$

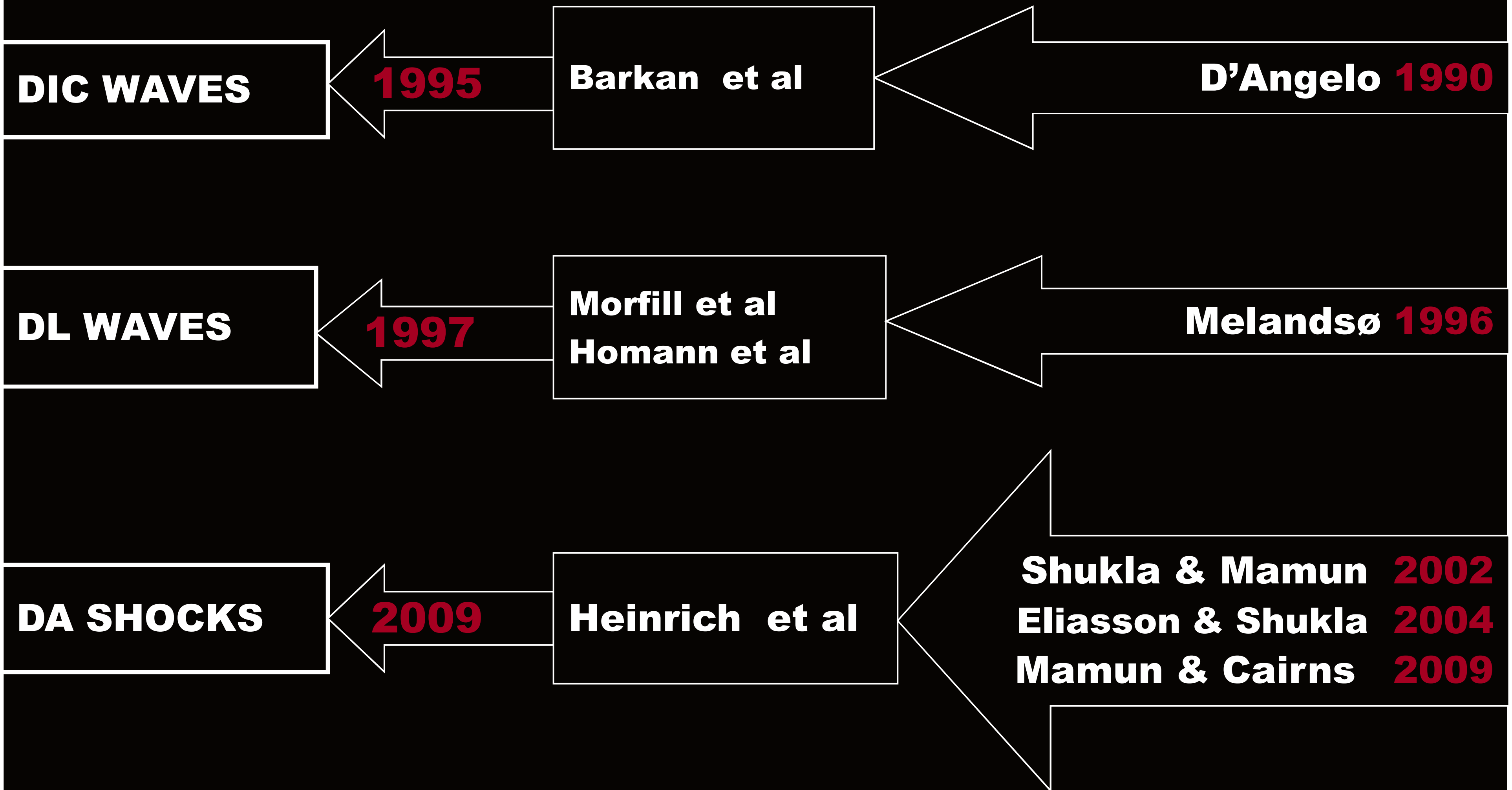
$n_d \sim 10^4$ cm-3

SS cylindrical chamber (kaolin dust at its bottom) is initially pumped down to a base pressure of 0.001 mbar by rotary pump.

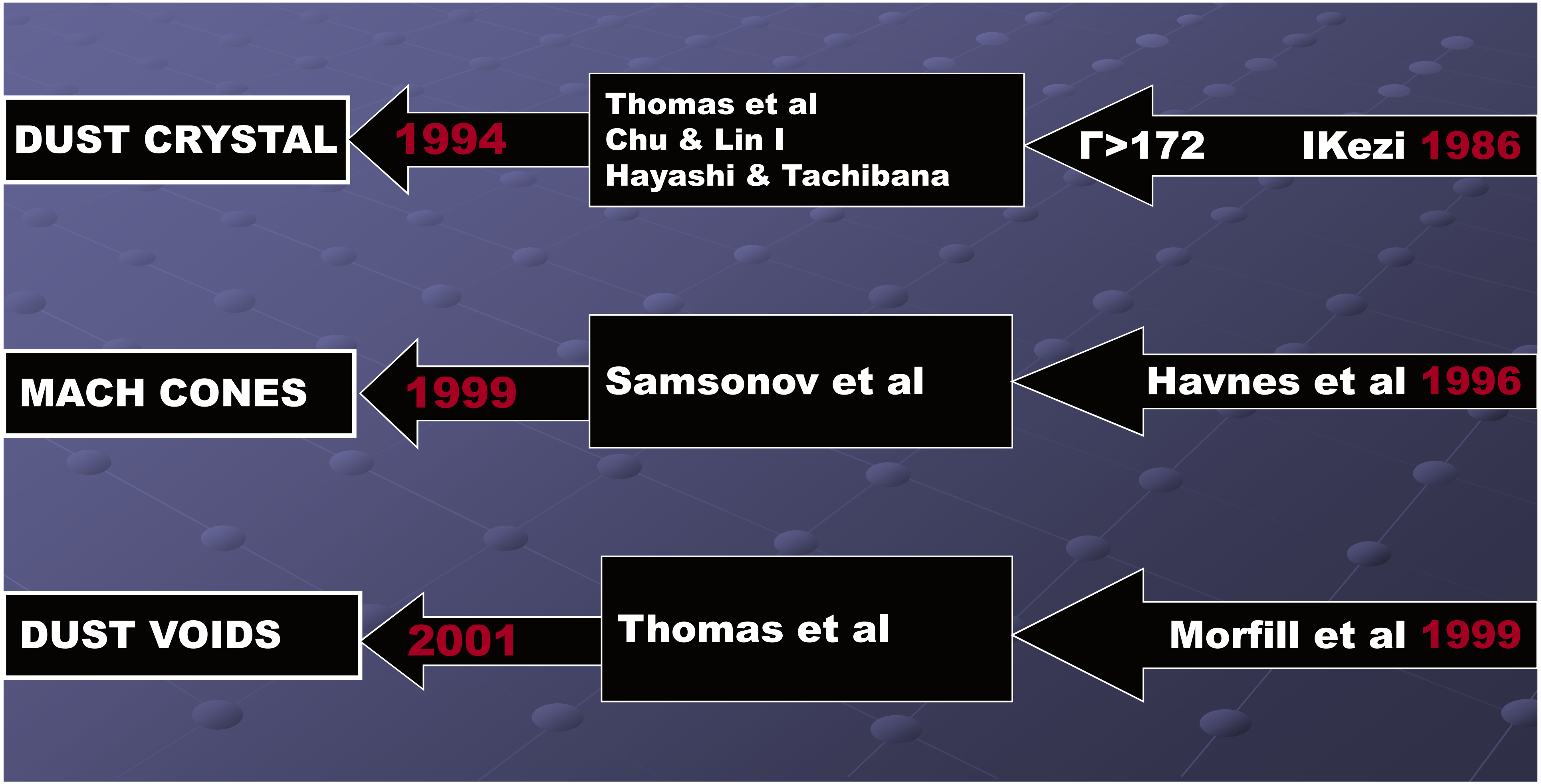
It is then purged with Ar gas using a precision needle valve, and subsequently pump down to base pressure. This process is repeated several times, and pressure is kept constant at 1 mbar.

A discharge is then produced between rod-shaped anode & ground vessel at an appl. voltage of 600V. A dense dust cloud is formed by reducing appl. voltage to 542V & neutral gas pressure to 0.09 mbar.

- We have discussed theoretical and experimental observations of waves in unmagnetized and weakly coupled dusty plasmas. However, there are some other discoveries of waves in magnetized or strongly coupled dusty plasmas. These are, for examples:



- The discoveries in dusty plasmas are not limited to waves only. There are many other remarkable discoveries in dusty plasmas particularly, in strongly coupled dusty plasmas. The some of them are:



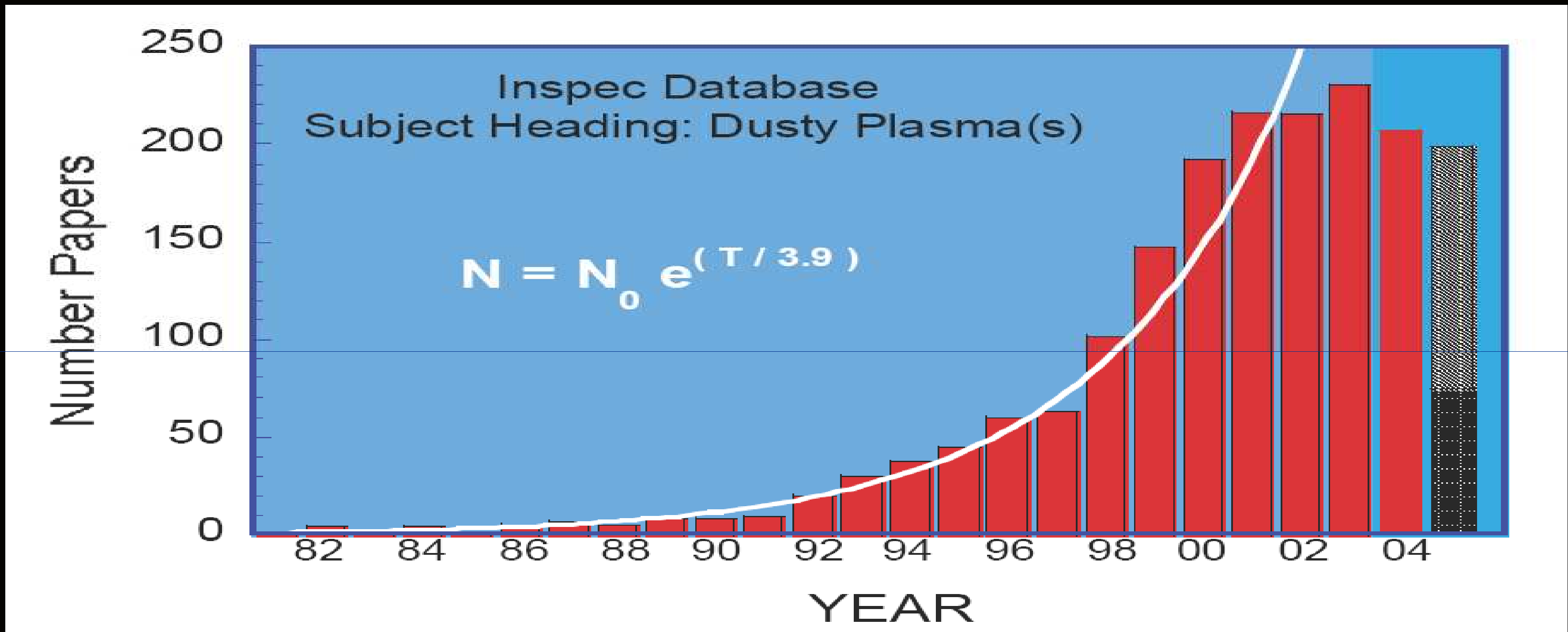
## ❑ SUMMARY

- Dust is almost everywhere, and there is no branch of science where the physics of dust is not directly or indirectly involved.
- Our universe is full of dust. So, we cannot explain the physics of our universe without the role of dust.
- The physics of mobile/immobile dust, which have variable size, charge and mass, arises unsolvable complexities and makes the field of DPP infinitely large.
- Dust do not only modify the existing plasma wave spectra, but also introduce new waves, e.g. DIA, DA, DL, etc. The physics of these waves must play an important significant role in understanding the properties of localized ES/EM structures in space/laboratory dusty plasmas.

- There are many remarkable experimental discoveries (e. g. given bellow) which have made the field of dusty plasma physics very exciting:

| Discovery | Year | Experiment | Theory |
|---|---|---|---|
| DUST CRYSTAL | 1994 | Thomas et al<br>Chu & Lin I<br>Hayashi & Tachibana | Γ>172 ← IKezi 1986 |
| DA WAVES | 1995 | Barkan et al | Rao, Yu & Shukla 1990 |
| DIA WAVES | 1996 | Barkan et al | Shukla & Silin 1992 |
| DL WAVES | 1997 | Morfill et al<br>Homann et al | Melandsø 1996 |
| MACH CONES | 1999 | Samsonov et al | Havnes et al 1996 |
| DUST VOIDS | 2001 | Thomas et al | Morfill et al 1999 |

- **Dusty plasma physics is a very rapidly (exponentially) growing research field. This is obvious from the figure below):**




- **To conclude: for its infinitely large domain, versatile applications and unsolvable complexities, the field of DPP has become a challenging research topic not only for near future, but also for a long --- long --- period of time to come.**

# THANK YOU ALL