IPR, Gandhinagar

Atmospheric pressure plasma and its application in textile and polymers

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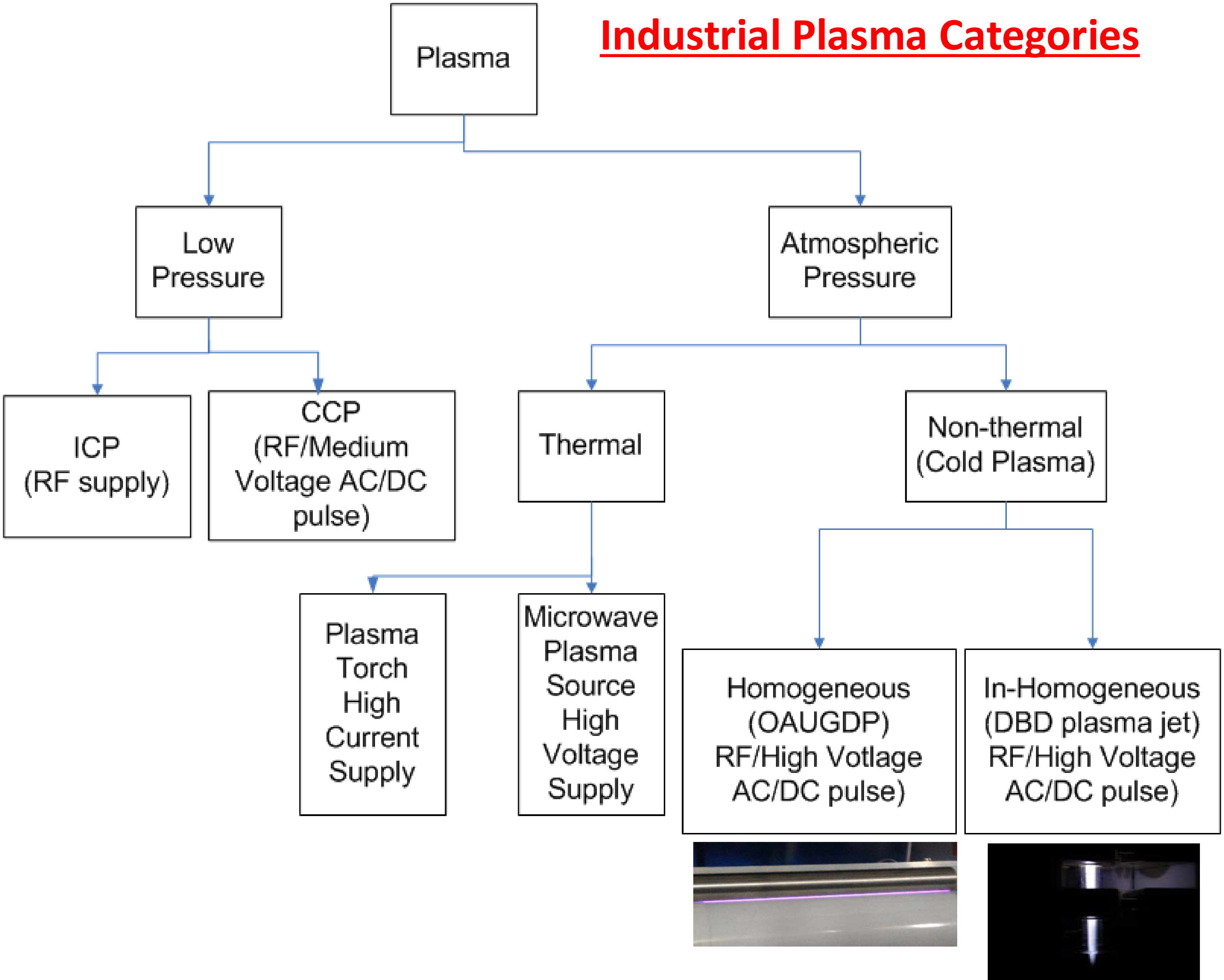
Outline of the presentation…

- Why plasma processing of textile?
- Industrial plasma categories
- Introduction to DBD plasma
- International status
- Indian Status of textile plasma technology
- Challenges in designing inline air plasma treatment system for textile processing
- IPR’s approach for developing a streamer free DBD plasma treatment system in India
- Various laboratory tests results on various textiles
- Cost economics of plasma technology in India
- Summary

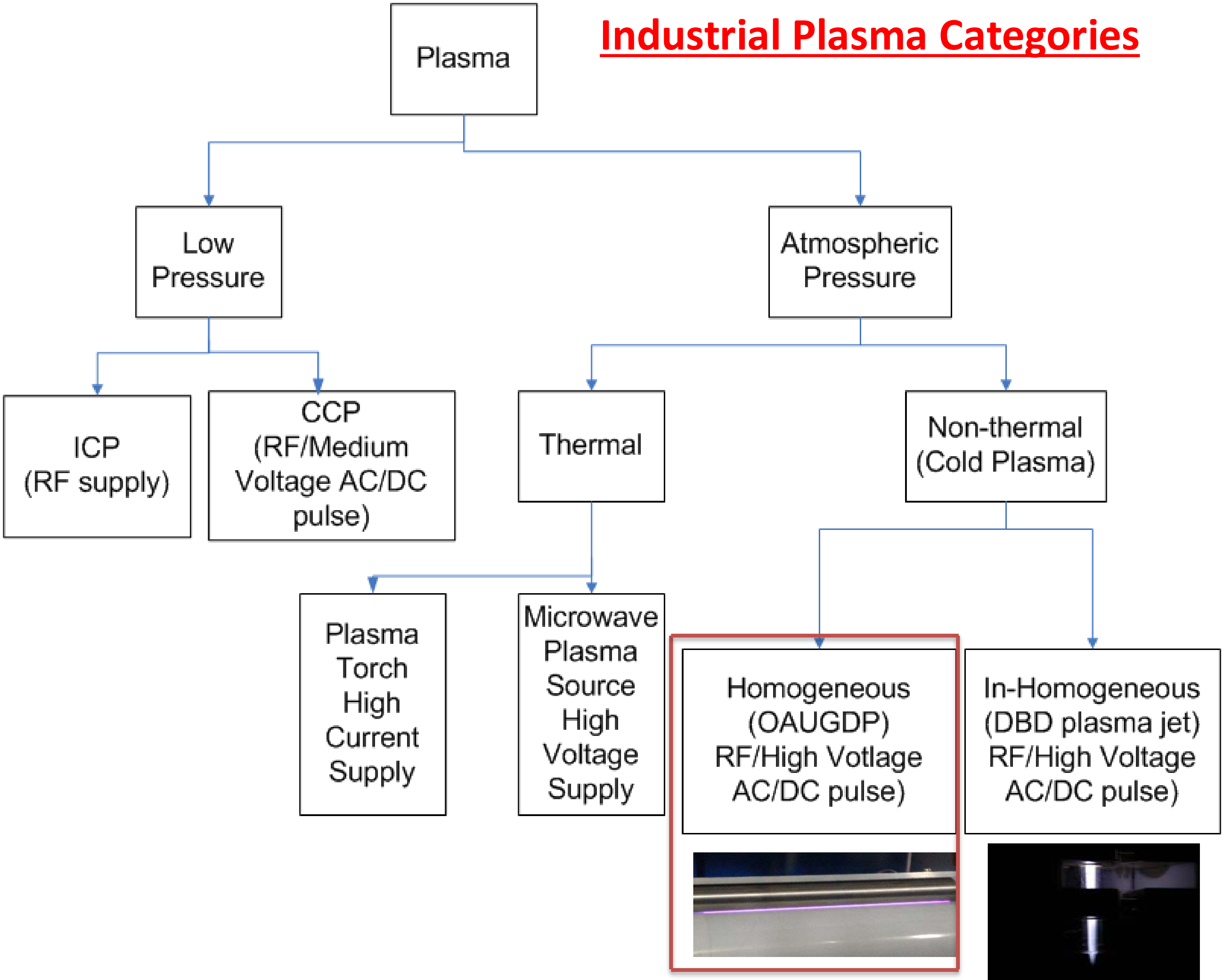
Why Plasma Processing of Textile?

S. No.	Chemical Process	Plasma Process
1.	Wet process (Huge quantity of water is required)	Dry process (no water is required)
2.	Uses hazardous chemical like Chlorine etc	Uses Air (most demanded) or any inert gas
3	Chemical waste generated which is a big environmental threat	Environment friendly process
4	Slow process as it involves drying or heating before further processing	Fast process. Further processing can be done immediately.
5	Creates functional groups on surfaces	Most importantly it can create same functional groups on surfaces hence it can easily replace hazardous chemical process

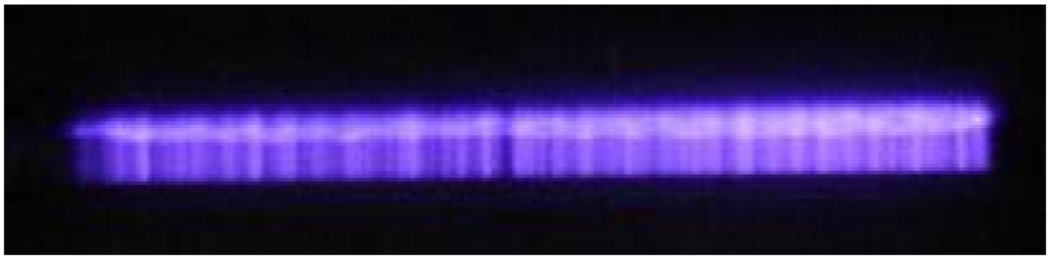
Industrial Plasma Categories



Industrial Plasma Categories

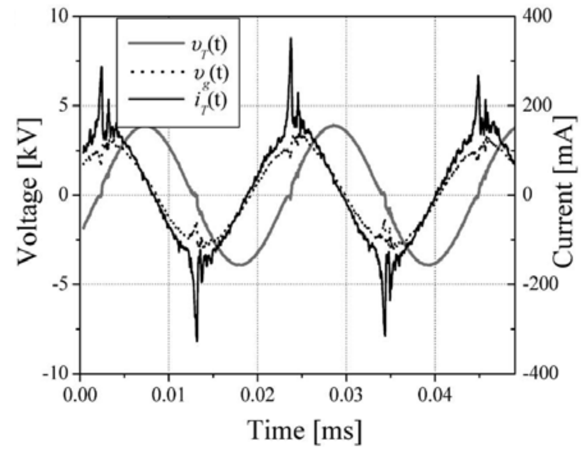


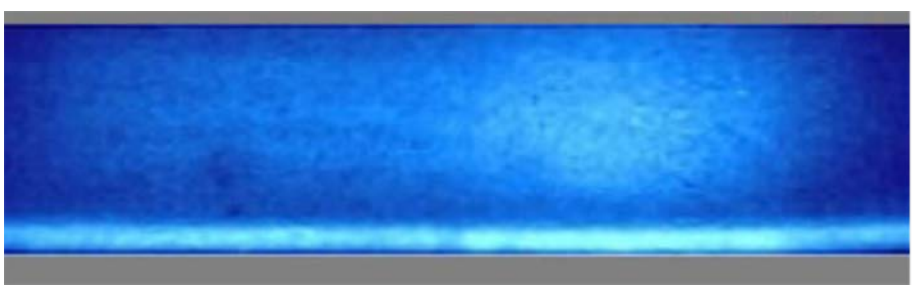
Introduction to DBD plasma



Filamentary Discharge

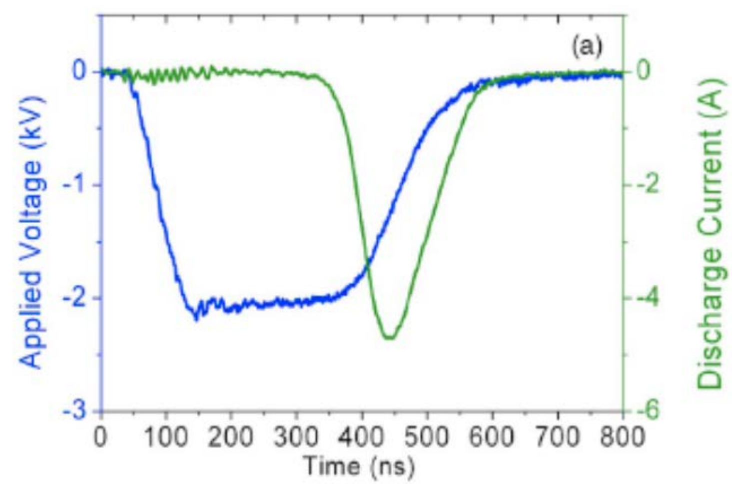
V-I Waveform under filamentary discharge in 50Hz source





Uniform Glow Discharge

V-I Waveform under diffused discharged under Nanosecond Pulsed source



J.L.Walse, J.J.Shi, M. G. Kong, Applied Phys. Lett. 89, 161505 (2006)

International Status

- Surface Activation Corporation (USA), Belmont, California (USA)
- Fraunhorf IGB (Stuttgart, Germany), Polyplas (Emmerthal, Germany)
- NIEKMI Institute in Russia along with Pavlolo Posad Shawl Manufacturing Company, Techno-plasma (Joint work by NIEKMI and several textile machine manufacturer
- H.T.P. Unitex in Italy
- Europlasma (Oudenaarde, Belgium)
- Softel electronics (Germany), Sherman Treaters Co. (UK)

Limitations:

- Limited to vacuum system,
- lower productivity
- high speed operation
- cost due to use of He

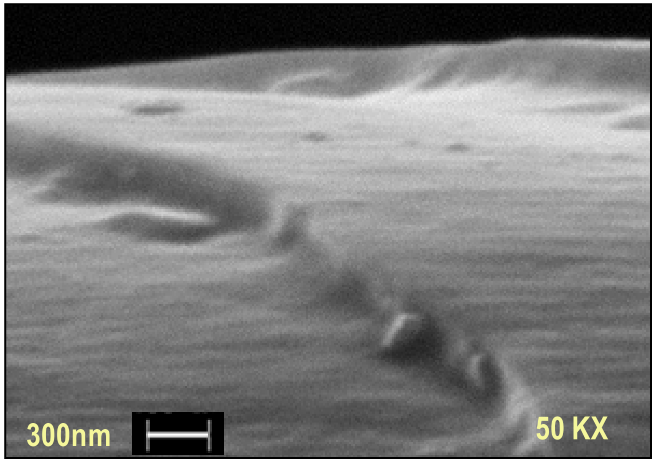
Dow Corning Plasma Solutions and Apjet inc are the only available APGD Plasma machine manufacturer for textile applications in the world

Indian Status of Textile Plasma Technology

Angora Wool Treatment

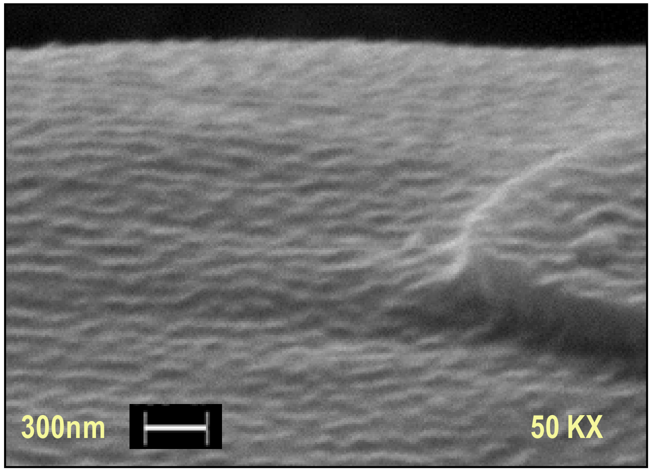
Improved Spinnability of Fibers

- Angora wool- Obtained from Angora rabbits
- Eight times warmer than sheep wool.
- Fiber very soft & slippery could not be spun.
- 100 % Angora wool processing was not possible.



Atmospheric Pressure Air Plasma

SEM Analysis



Coefficient of Friction (μ) for Angora Wool Fiber	
Untreated	0.08
Air Plasma Treated	0.2-0.3

100% Angora Product

Breaking Strength (cN/denier) for Angora Wool Yarn	
Untreated	0.3
Air Plasma Treated	2.03

- Only Electricity as consumable
- Maintenance Free
- Processing Cost ~ 40 Rs/Kg

Installed at

a. HIFEED Ranichauri, Himanchal Pradesh, India
b. KHWCIS Kullu, Himanchal Pradesh, India
c. SHHDC Sikkim, India
d. Wool Research Association, Mumbai

Features:

1. **Treats Angora wool satisfactorily**
2. **10 kV, 50 Hz supply**
3. **Dielectric as a conveyor belt**
4. **Continuous treatment system**

Plasma Reactor has been installed at Kullu, Himachal Pradesh, India

Limitations:

1. Slow treatment speed (4.5 meter per minute)
2. Dielectric breakdown with increasing power density

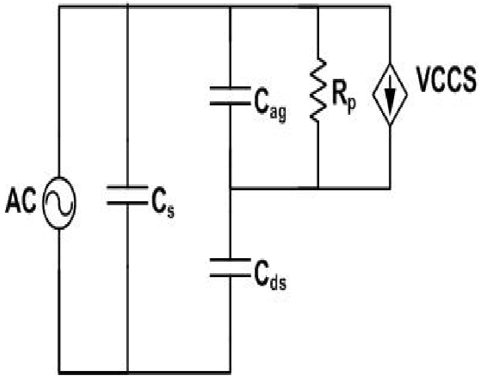
Application of plasma treatment in Artificial leather production

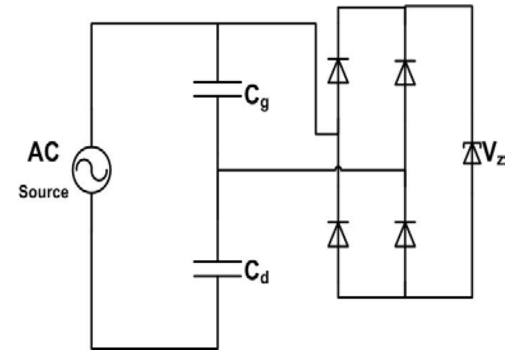
A plasma system for treatment of polyester film to increase adhesion with PU, PVC to make artificial leather in 2014 (Commissioned in Surat, India)

There was 30% increase in Peel-of-Strength from 5.25 kgf/mm to 6.9 kgf/mm after the air plasma treatment.

Challenges in Designing Inline Air Plasma Treatment System for TEXTILE processing

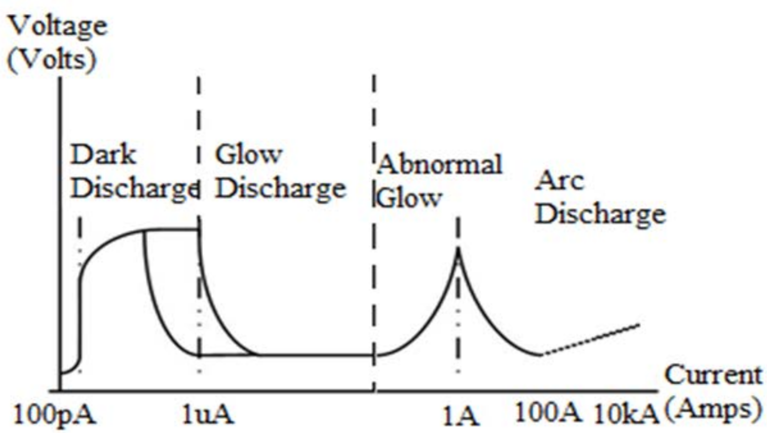
- Safe and streamer free uniform glow discharge plasma at atmospheric pressure over a large textile surface
- Generation of Air Plasma in instead of using costly gas medium like helium and argon.
- High density plasma discharge for fast and Inline treatment.
- Continuous 24 x 7 plasma discharge as required in textile industries.
- Economic viability (capital as well as operating cost).
- Compactness so that it is easy to handle and maintain.

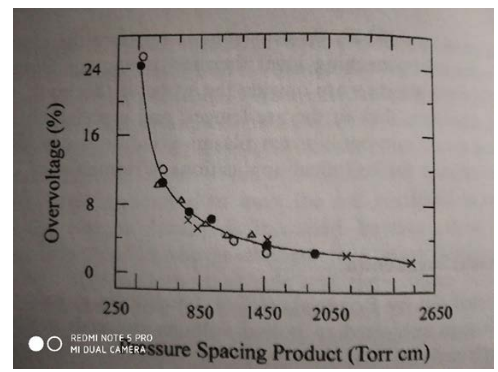


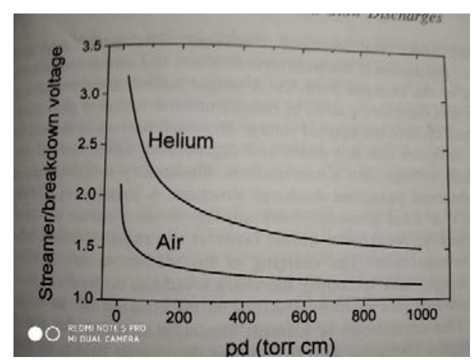


Nonlinear DBD model

Generalized Linear DBD model

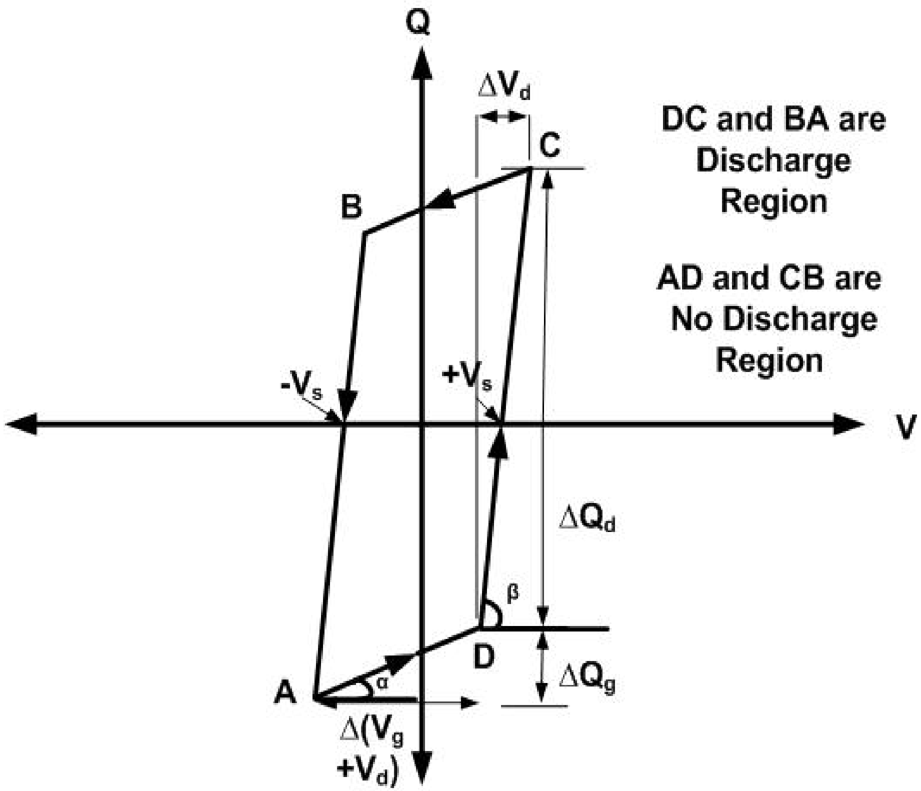


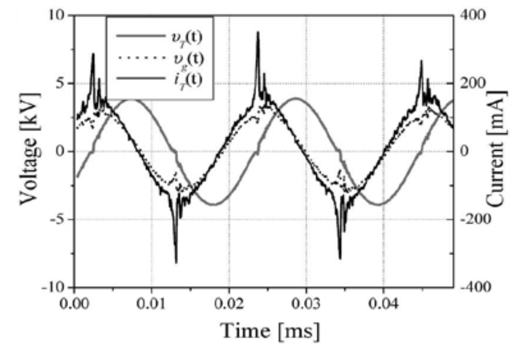


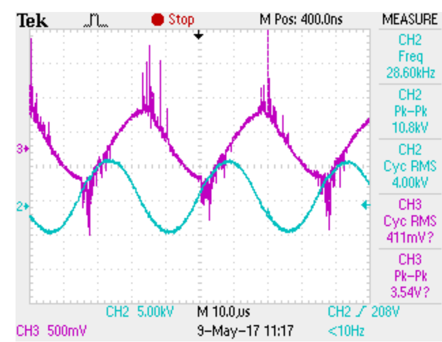


Townsend DC Discharge Characteristics

Source: Becker et al. "Non-equilibrium air plasma at atmospheric pressure"



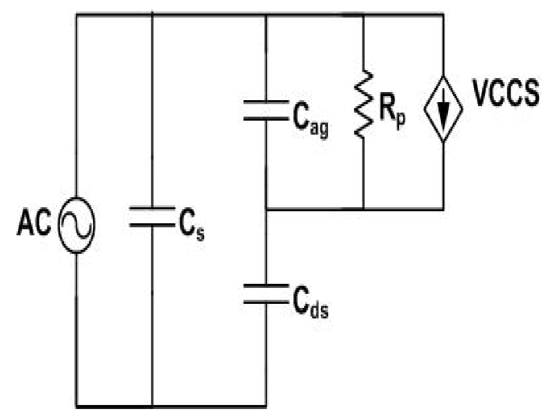




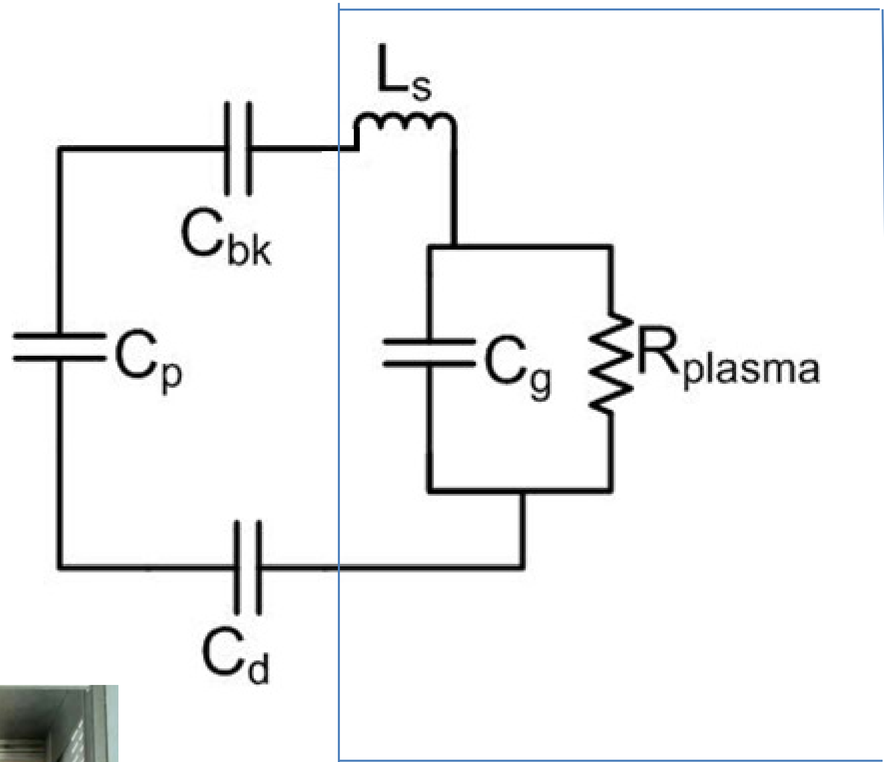
$$I_{ccs} = (1+\frac{C_g}{C_d})I_d - C_g\frac{\partial V_a}{\partial t},$$

where I_d is the current flowing through the dielectric.

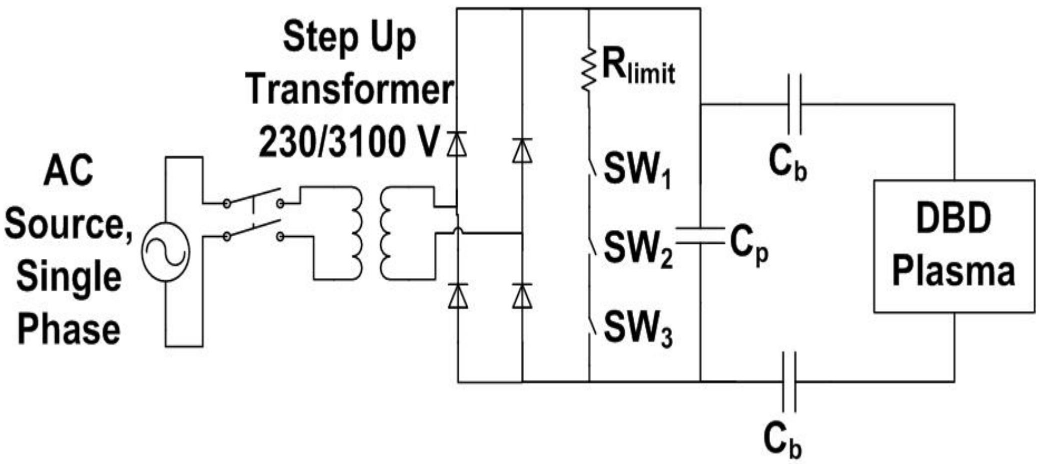
$$I_d = i(t) - C_s\frac{\partial V_a}{\partial t},$$



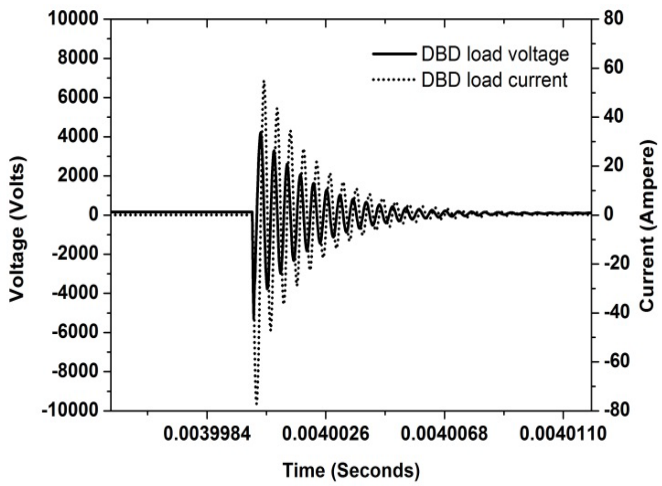
IPR's approach for developing a streamer free DBD plasma treatment system in India



Envisaging a tank circuit comprising stray inductor in it to generate RF oscillations in air gap model

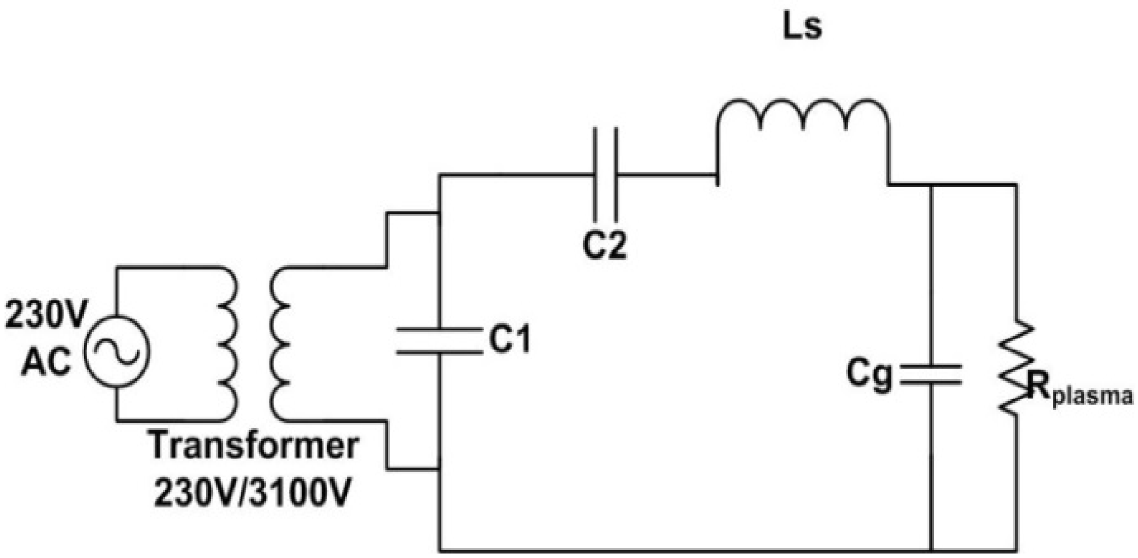


Use of Bridge rectifier for enabling IGBT operation



Diode current in MATLAB Simulation

Mode 1: Capacitor C_1 Charging through line voltage in an half cycle (rectifier is not shown)



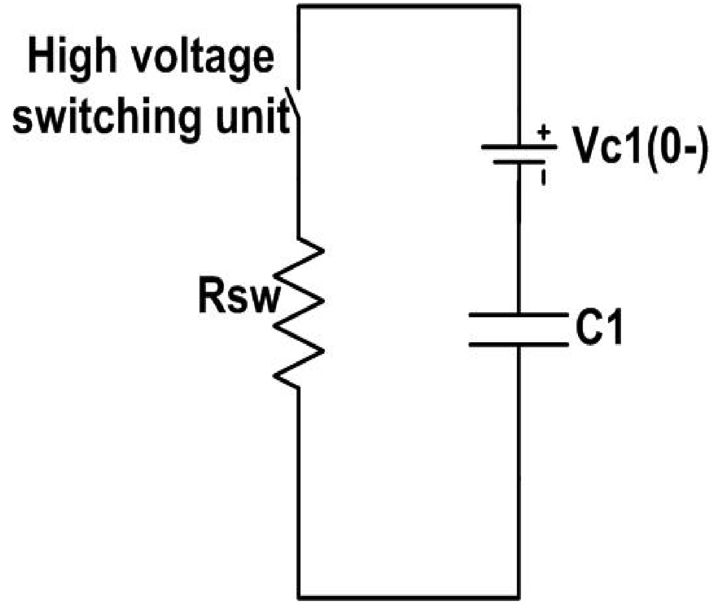
$$C_t = \frac{C_2 C_g}{C_2 + C_g} \text{ and } C_2 >> C_g,$$

$$\text{Hence}, C_t \cong C_g$$

$$i(s) = V_m \omega C_1 [\frac{S}{(S^2 + \omega^2)}],$$

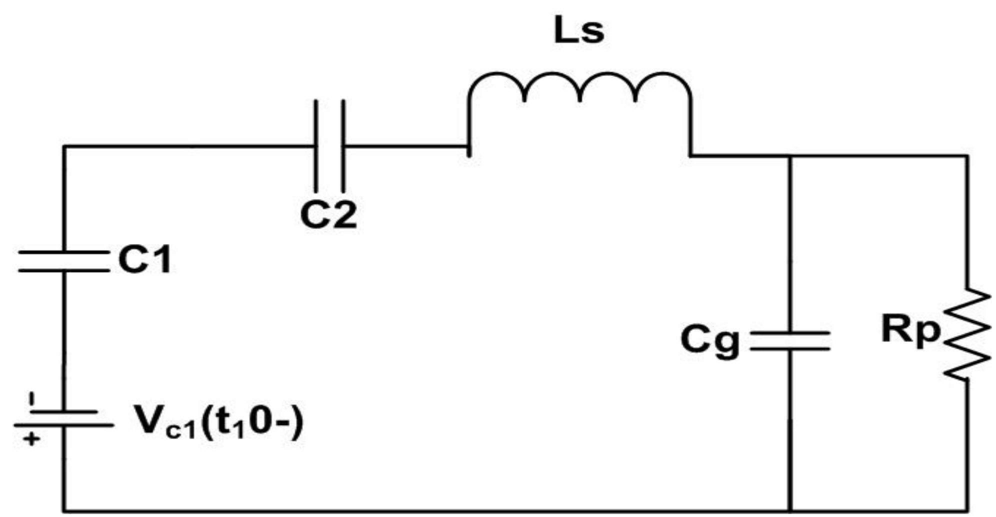
$$i(t) = V_m \omega C_1 \cos(\omega t),$$

Mode 2: Capacitor C_1 Discharging through line voltage



$$V_{c1}(t) = V_{c1}(0-)[1 - e^{\frac{t}{R_{sw}C_1}}],$$

Mode 3: Capacitor C_1 Discharging is suddenly opened due to which a ringing oscillations are generated forming DBD plasma in air gap.

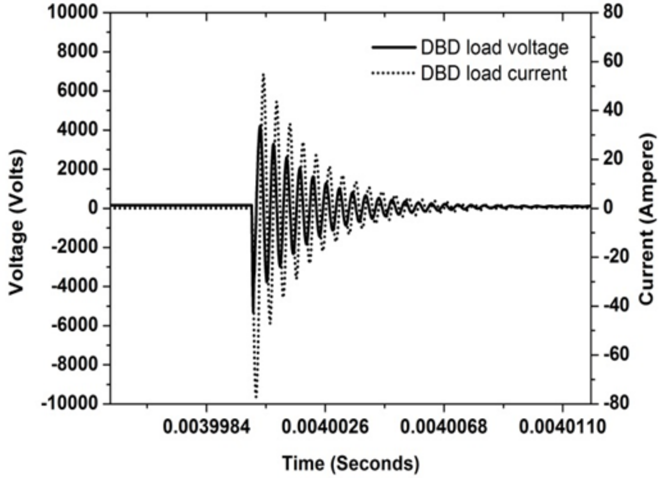


$$i(s) = \frac{V_{c1}(t_1 0-)}{L_s}\left[\frac{(S+K)}{(S^3 + S^2K + 2\omega_n^2 S + 2K\omega_n^2)}\right],$$

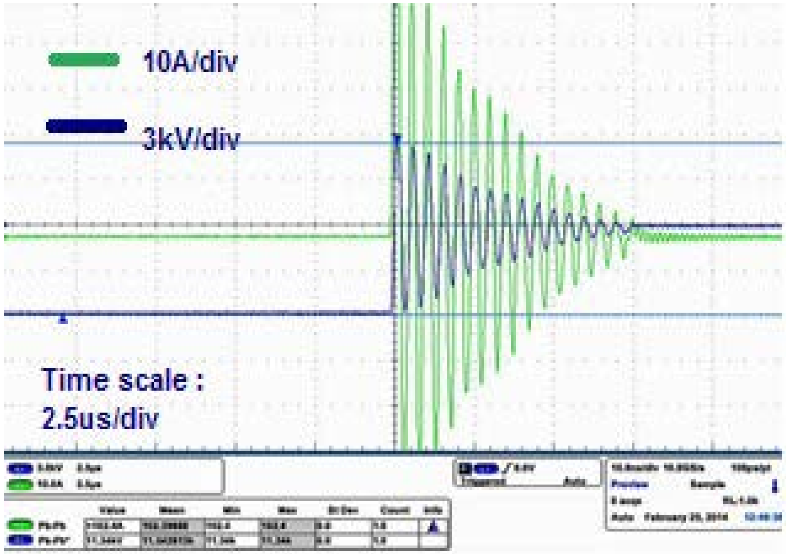
$$\text{where } K = \frac{1}{R_p C_g} \text{ and } \omega_n^2 = \frac{1}{L_s C_1},$$

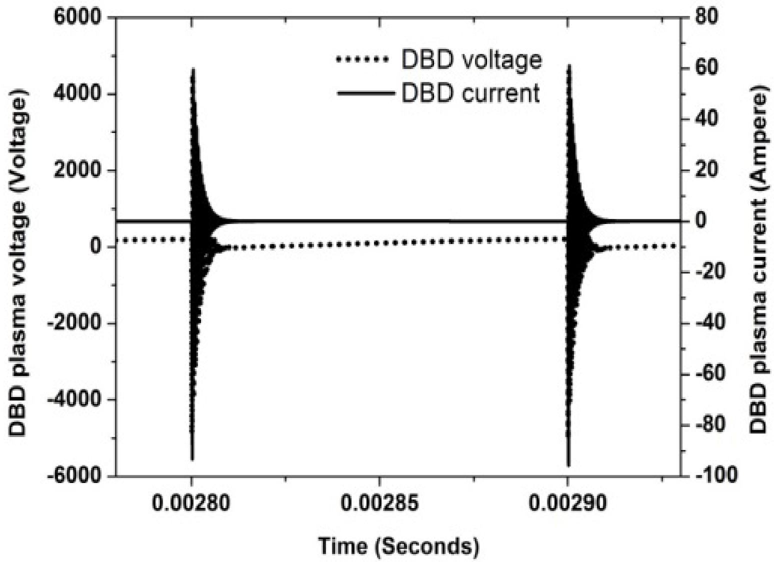
$$i(s) = \frac{V_{c1}(t_1 0-)}{L_s}\left[\frac{1}{(S^2 + 2\omega_n^2)}\right],$$

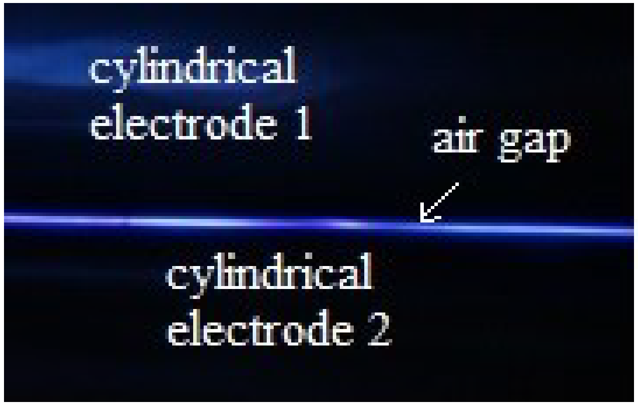
$$i(t) = \frac{V_{c1}(t_1 0-)}{\sqrt{2}\omega_n L_s}\sin(\sqrt{2}\omega_n t),$$



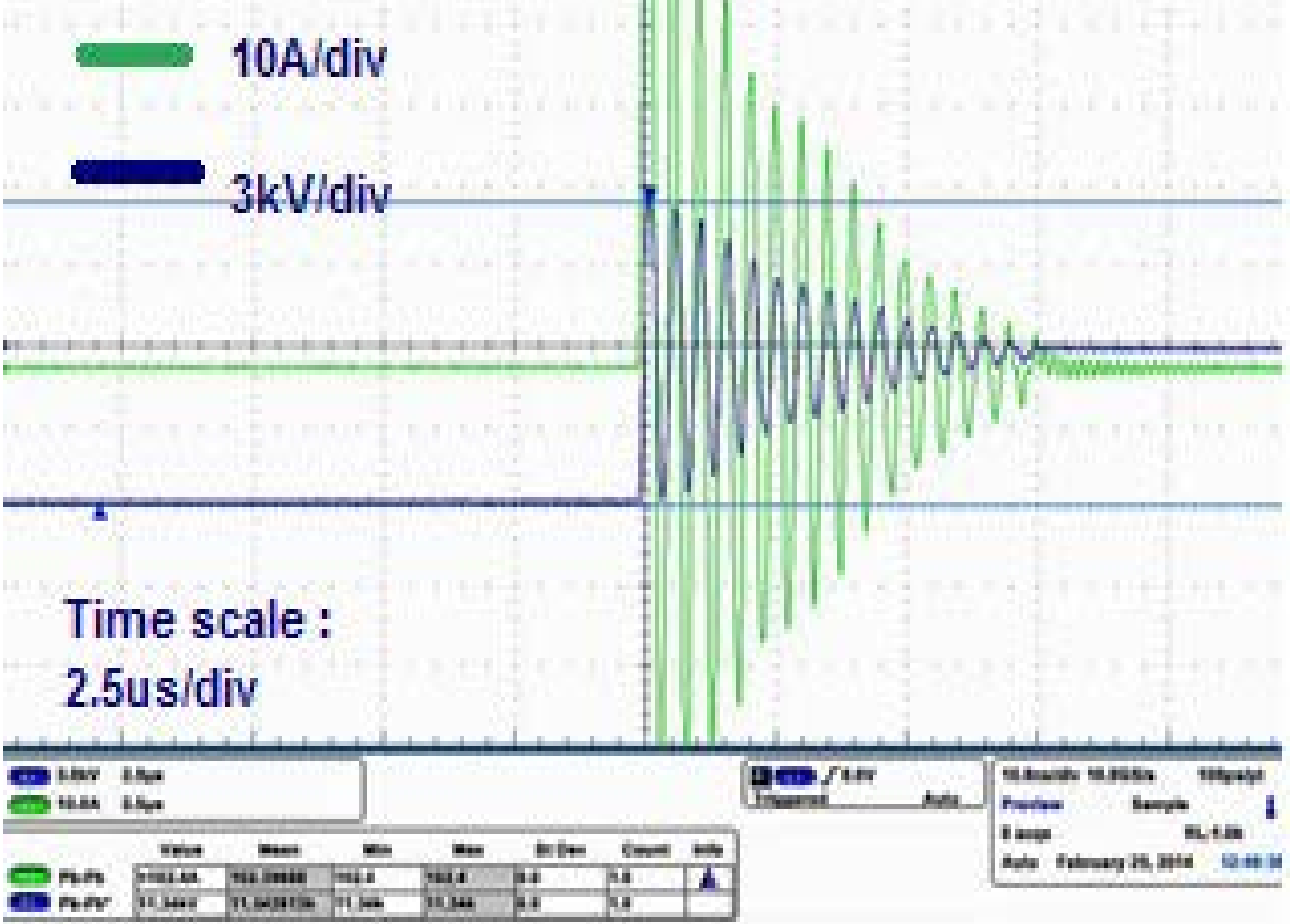
Simulated Voltage and Current

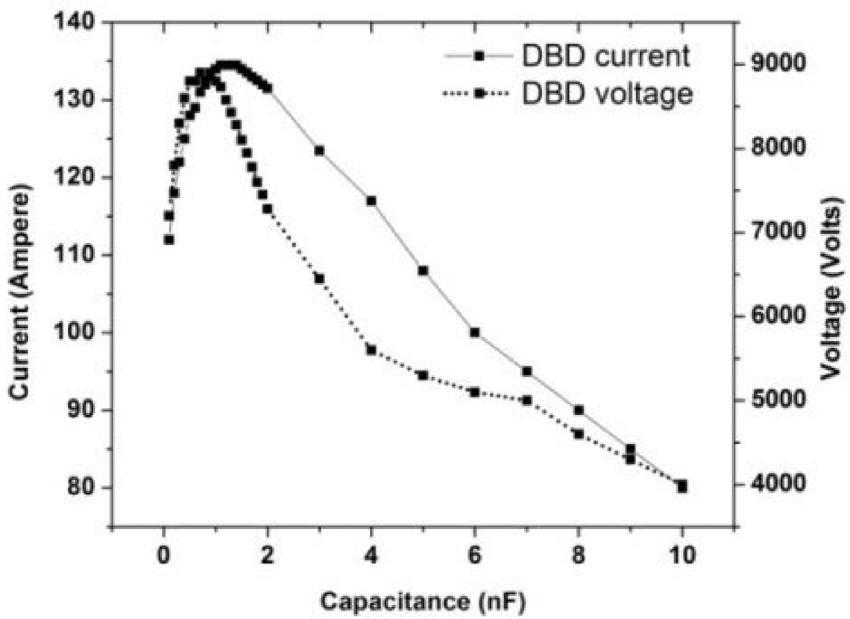


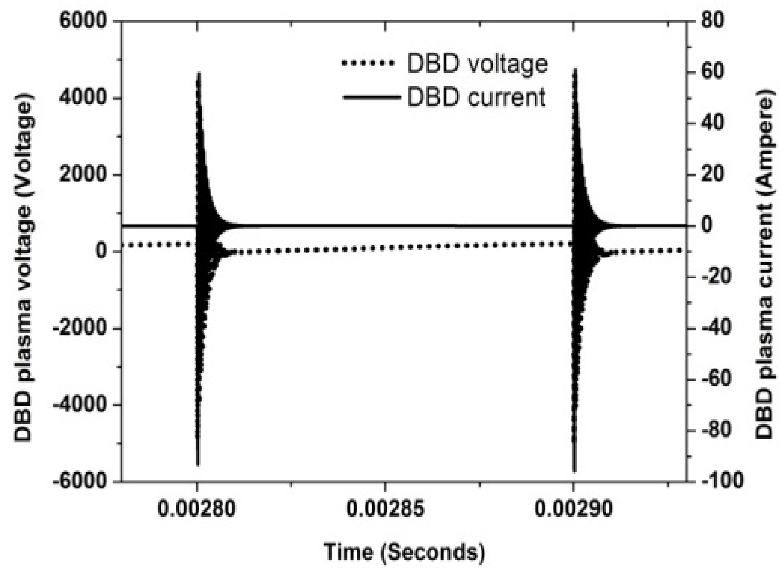




Topology for Generating Uniform Glow Discharge Plasma

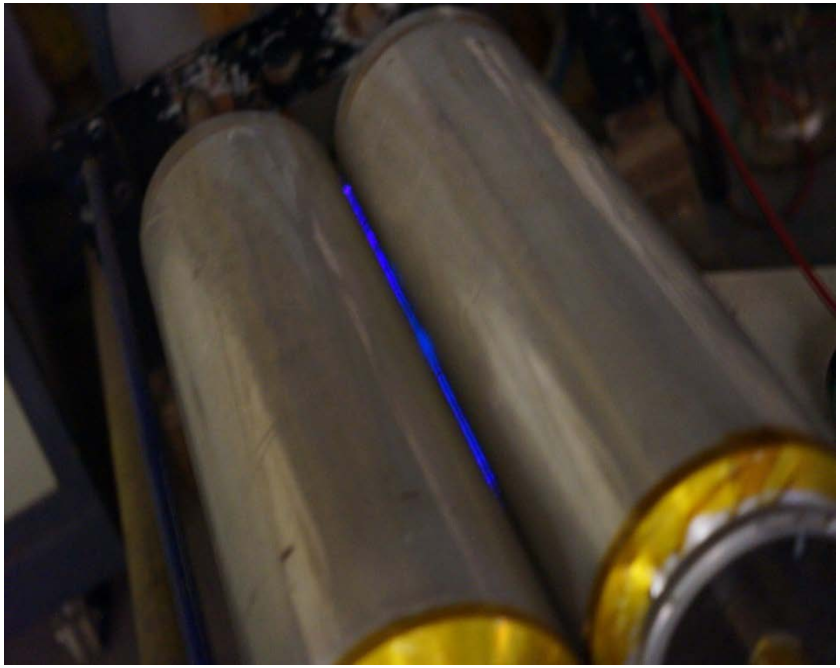




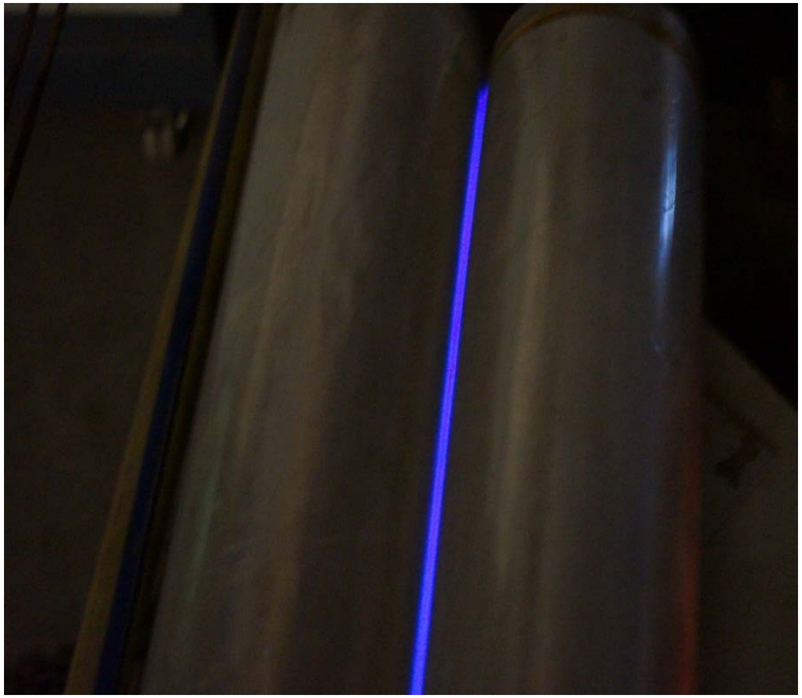


Effect of capacitor C_1 on output voltage and current

Repetition of DBD plasma discharge in Simulation



Filamentary discharge using conventional HV low or medium frequency power supply



Uniform Glow Discharge using designed power source

Indian Patent grant number: 408755
Publication: v. jain et. al., Review of Scientific Instruments, vol. 89, no.3, p. 033502

2.5 meter length Uniform Glow Discharge Line Plasma

Plasma System for Textile Treatment, Surat, India

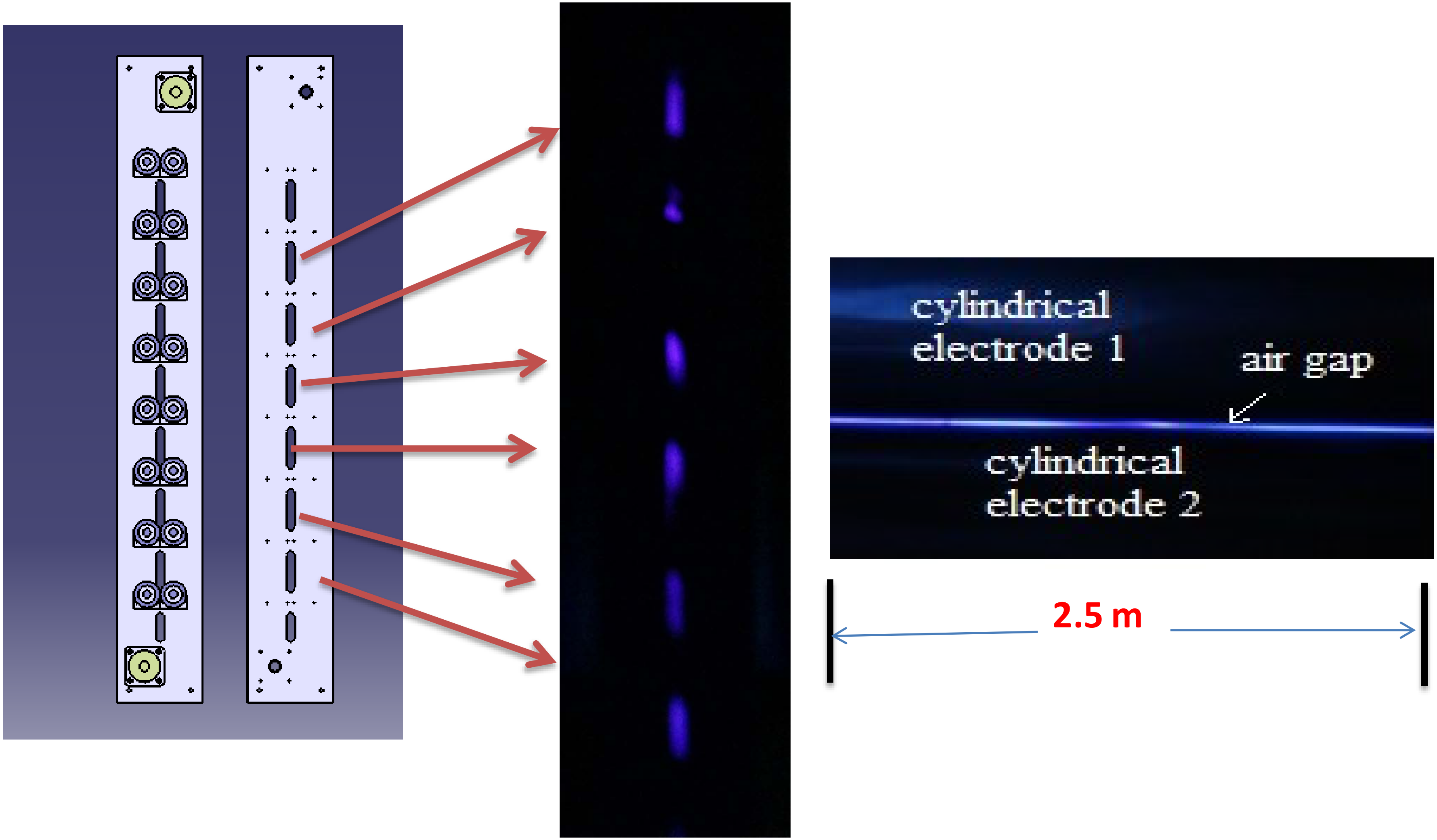
Dimension:
8 m x 3 m x 2.5 m

A project funded by DST, New Delhi and MANTRA Surat for "Design and development of plasma system for inline treatment of textile at moderate speed"

Plasma Treatment System for Inline Textile Treatment commissioned at MANTRA, Surat, India in March 2019

Features:

- **The system generates air plasma using dielectric barrier discharge technique and a specific power supply for plasma generation.**
- **This system generate uniform plasma over a 2.5 meter wide electrodes pair and There are 72 nos of such electrodes' pairs which are powered using separate individual low cost power supply designed at IPR in India.**
- **This is apparently world's first large scale air plasma system for textile treatment.**

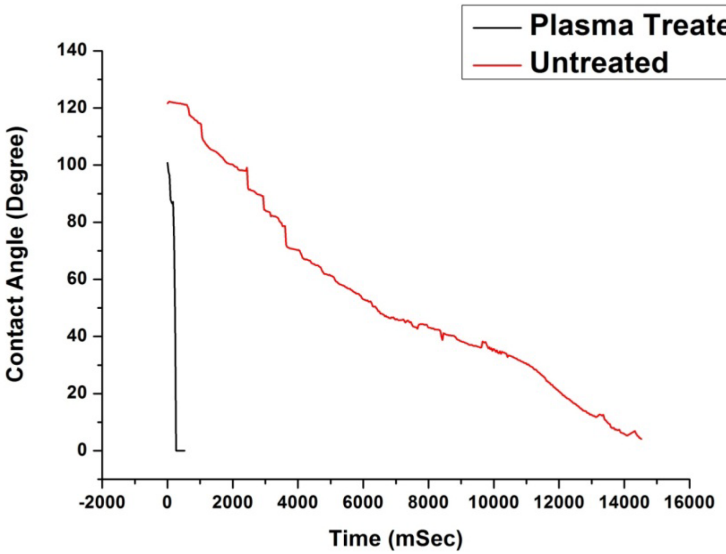

cylindrical
electrode 1
air gap
cylindrical
electrode 2
2.5 m

Results and Discussions

Application of this plasma in surface treatment of the followings were carried out:

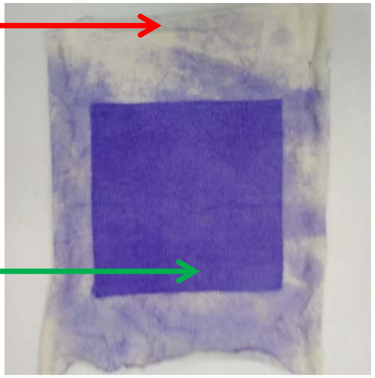
1. Grey cotton
2. PE film
3. PET film
4. Merino wool fibre
5. Polypropylene film
6. HDPE film

Results - Cotton Fabric (Laboratory scale visual characterization)



Untreated Cotton

Plasma treated Cotton



Untreated portion

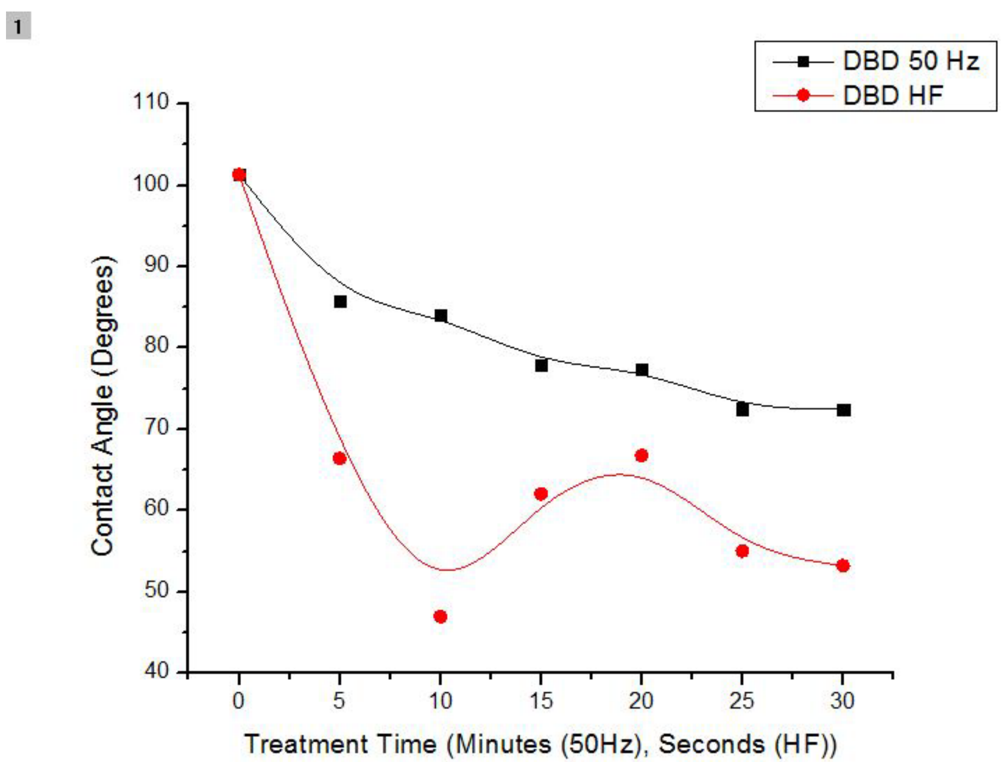
Results - Polyethylene (PE) film

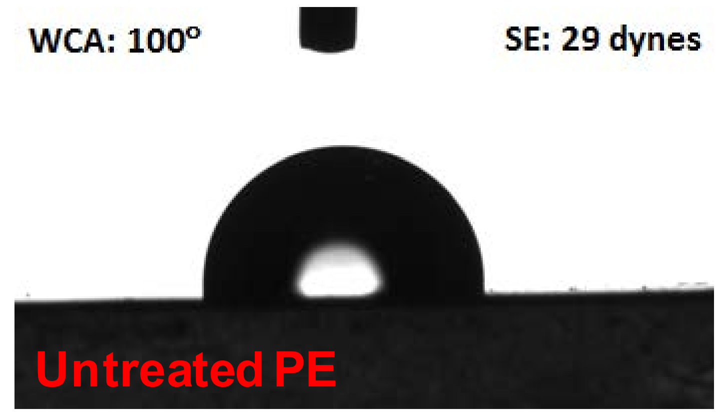
29 dynes/cm

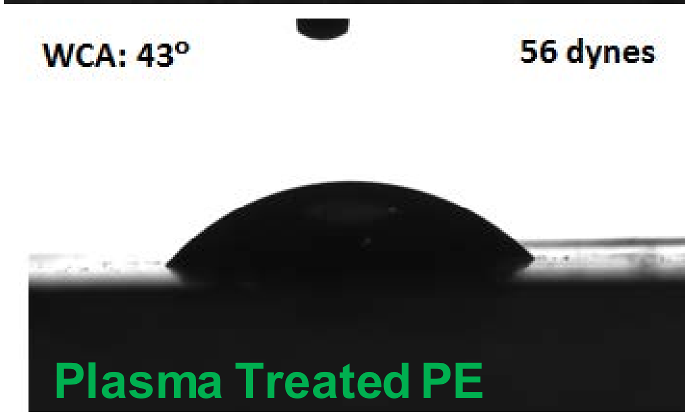
22-26 dynes/cm

Solvent Based Inks

35-38 dynes/cm

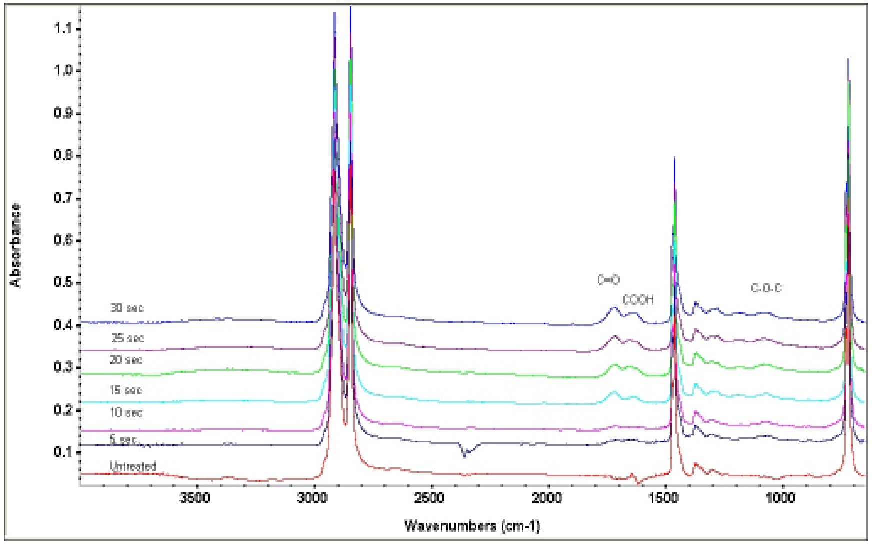




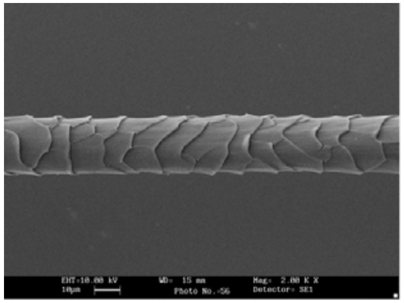
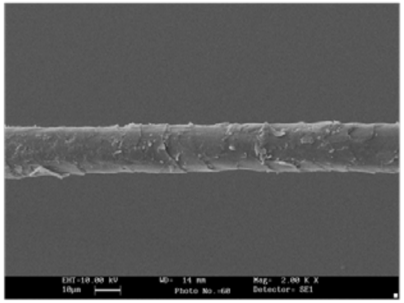
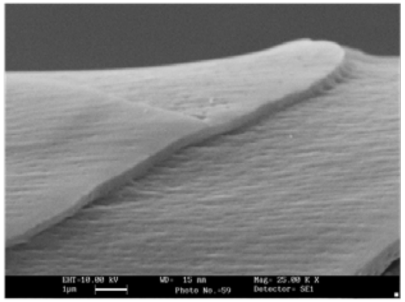
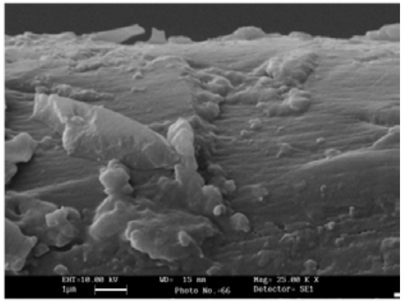


Results - PET film

FTIR Results



SEM Results

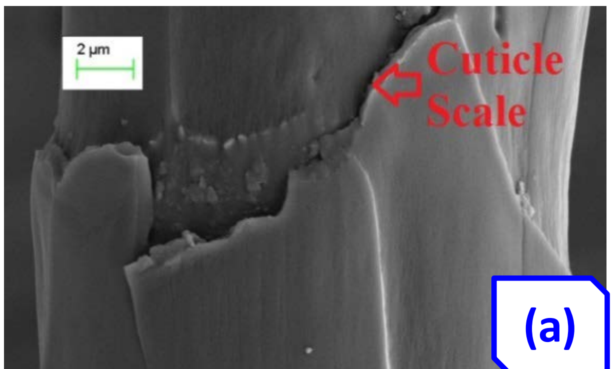





Merino Wool Treatment (15 Sec)

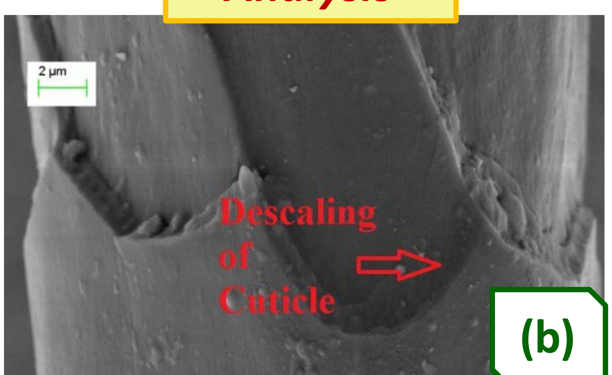
Results- Improving Anti-felting properties of Merino Wool Fibers

Felting- Entanglement of Fibers that leads to Shrinkage /Pilling of Woollen Garments. This is inherent property of wool due to hydrophobic scaly cuticle surface of the fiber.

Physical Etching



SEM Analysis



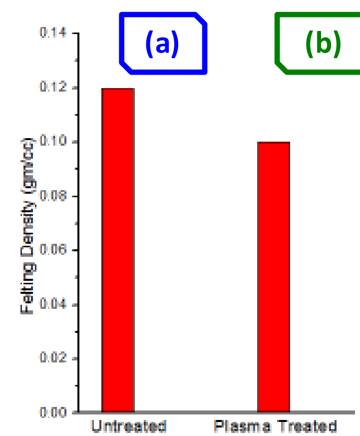
Chemical Modification

FTIR-ATR Analysis

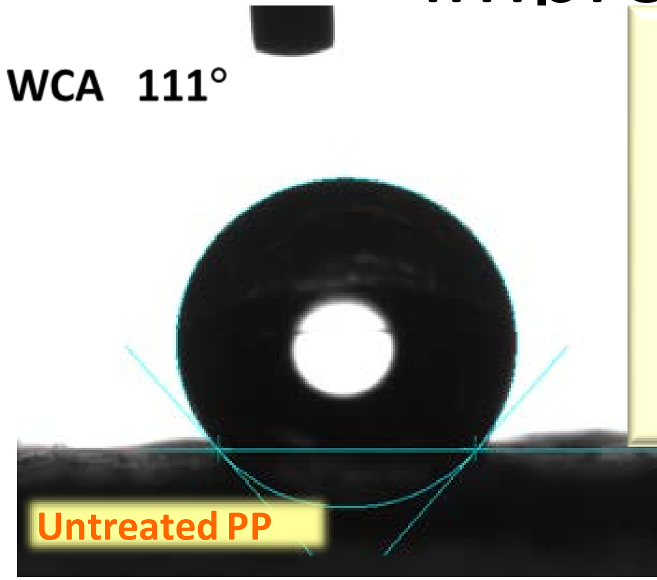
Species	Group	Absorbance Ratio: Untreated (a)	Absorbance Ratio: Plasma Treated (b)
Bunte's salt	(-S-SO_3)	0.38	0.98
Cysteic acid	(-SO_3-)	0.53	2.08

Felting Test : IWTO 2069

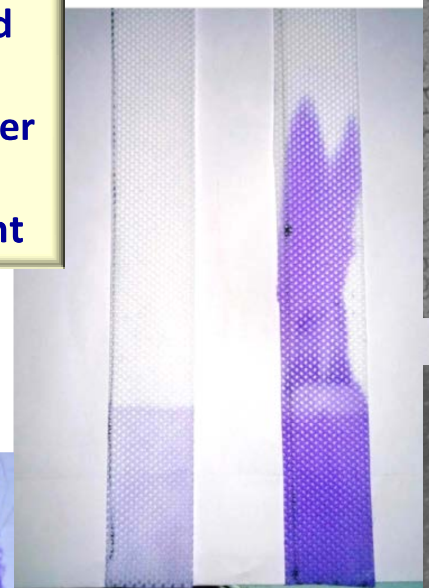
- **20% reduction in Felting Density by plasma treatment**
- **Enzyme/Resin Treatment after plasma surface modification is required to achieve results comparable to chlorination**

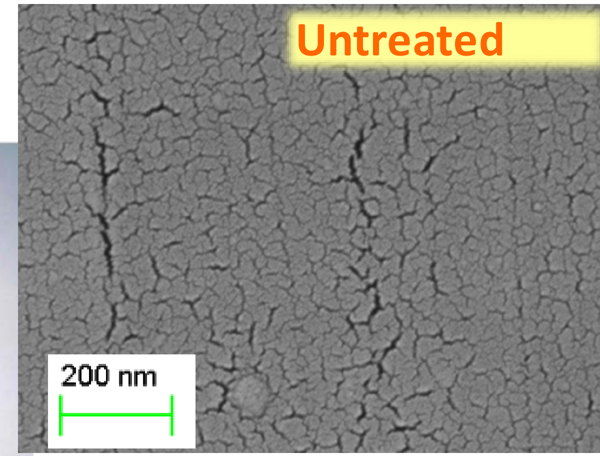


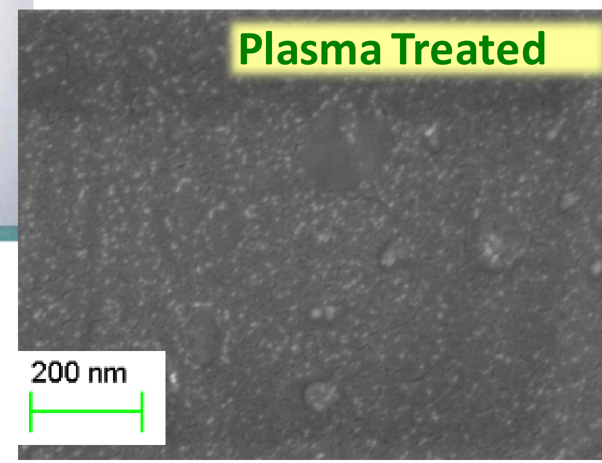
Polypropylene (PP) woven fabric for improving Hydrophilicity

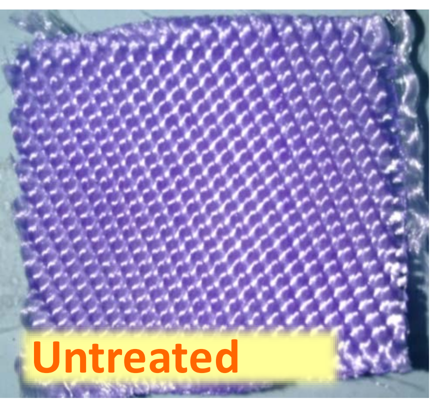


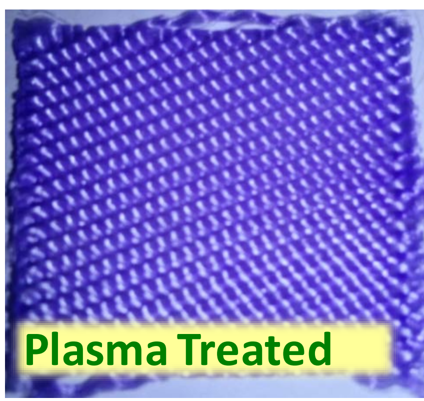
Vertical Wicking rate improved by 10 times after plasma treatment





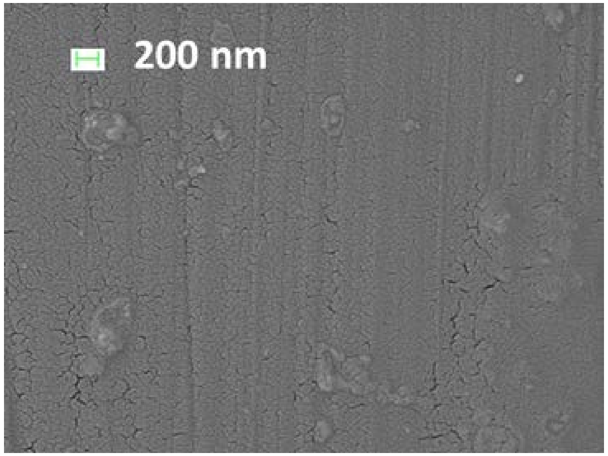




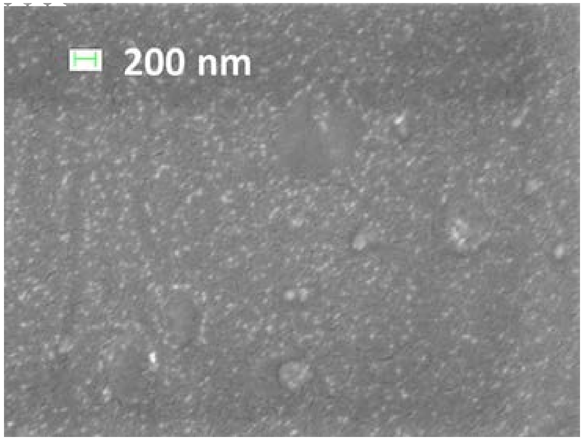


Results - Polypropylene (PP) film

SEM Image

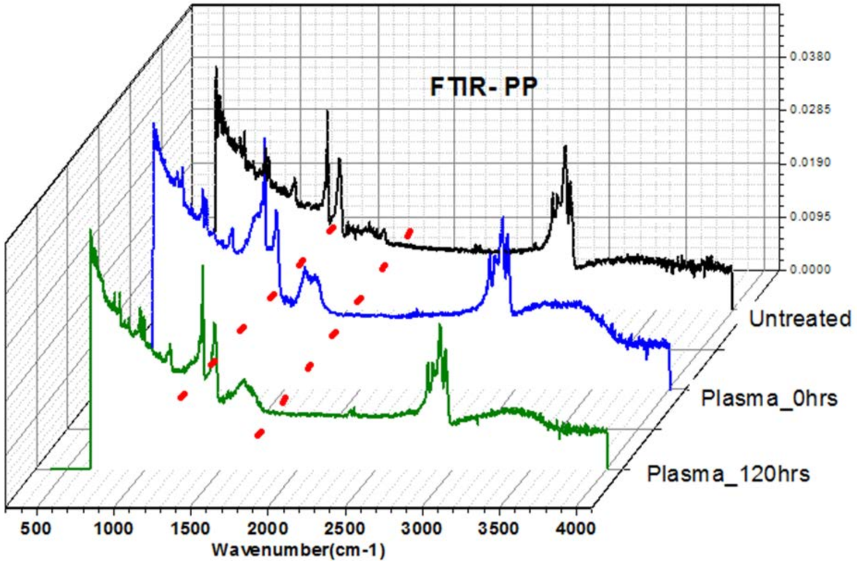


Untreated Polypropylene



Plasma Treated Polypropylene

FTIR of PP



Results - HDPE film

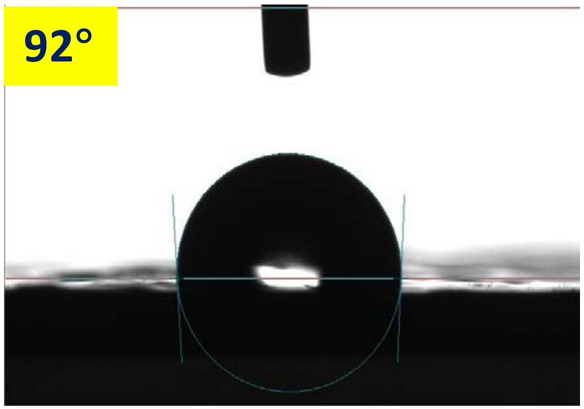
Results – A system was designed for a research institute in Plastic Engineering at Ahmedabad in 2019

Results - HDPE film

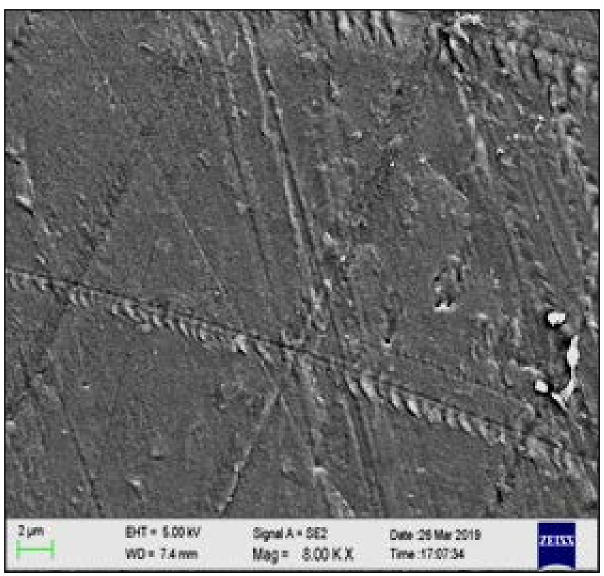
Untreated HDPE Film

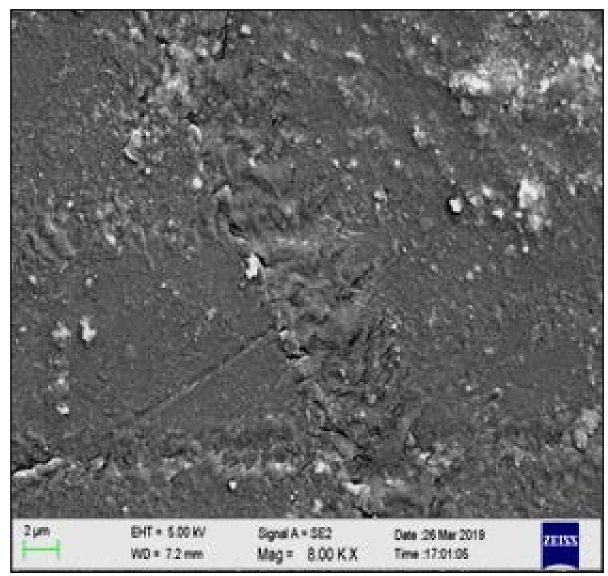
Plasma treated HDPE Film

Water Contact Angle Result



SEM Pictures





Cost Economics of Plasma Technology in India

- **Equipment cost** :
  - ~ 80 Lacs Rupees (**0.1 m USD**)
  - Consumables : No cost consumables only dielectric material may need replacement time to time.

- **Running cost:**
  - This system requires electrical power of 30kW for all the pairs of electrodes. In the system developed by IPR, if the target speed of minimum 20m/min is achieved. The cost of treatment of 20x 60x2.5 square meter would be = 30 x 7 Rs. Hence, the per square meter treatment cost would be **~ 0.07 Rs.**

Based on the literature survey, the cost of per square meter treatment for activation using plasma is **0.02 Euro** which is nearly **1.6 Rs.** (*source : Review paper on plasma treatment in textile industry by Andrea Zille, Plasma Process Polym 2014)*

Summary

1. The challenges in generation of uniform glow discharge DBD air plasma at atmospheric pressure has been successfully addressed at IPR.
2. This challenge was a major limitation of using plasma in textile industries.
3. It is well observed that plasma process is environment friendly process and hence, it has great potential in textile industries as against conventional hazardous chemical processes.
4. IPR has successfully built plasma systems for Angora Wool treatment for various locations in India.
5. IPR has built a large scale air plasma system for Inline treatment of textile at moderate speed for further data generation on various textiles.
6. IPR has built a system for HDPE treatment and supplied to a Plastic Engineering research institute in India.
7. Two Indian Patents have been granted.
8. The DBD air plasma technology has been transferred to two Indian industries.