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PLASMA PROCESSING UPDATE

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Content:

Industrial component enveloped by glow discharge during Plasma Nitriding Process

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Plasma Carburizing Process Developed at FCIPT

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While conventional gas carburizing has been the industrial backbone for hardening automotive gears for decades, it struggles with a number of consistency issues. The intricate geometry of modern gears, combined with the volume shifts that occur during high-temperature hardening, often leads to significant distortion. As the industry shifts toward global standards for higher fuel efficiency and reduced noise, minimizing these dimensional variations has become a priority. To address these challenges, plasma carburizing (a form of low-pressure vacuum treatment) has emerged as a superior alternative.

Plasma carburizing is a surface hardening process that involves the use of plasma (ionized gas) to introduce carbon into the surface of a metal, typically steel, to enhance its hardness, wear resistance, and fatigue strength. This process is a type of low-pressure carburizing that occurs in a vacuum chamber, and it offers several advantages over traditional carburizing methods. Plasma carburizing is performed by applying a voltage between the substrate table and chamber wall. The parts are heated in a vacuum furnace to austenization temperature (above 930 °C) and a carburizing gas (typically methane or propane or acetylene) is introduced at low pressure (7-10mbar) into the chamber for a short period of time (2 to 4 hrs).The carburizing period is often referred to as the boost step. After this step the steep concentration profile created during the short time is allowed to be "smoothed out" by diffusion. During diffusion, the plasma is switched off and the temperature is maintained at 860 °C. The parts are then quenched in gas, normally 6-20 bar of N_2 gas, or in oil. Since the plasma carburizing process is carried out in vacuum or with a carburizing or inert gas, oxidation doesn't occur. Problems that are encountered during conventional carburizing process are uneven carburization and oxidation. Plasma carburizing process eliminates these issues. Compared to the conventional gas process, plasma carburizing offers a clean, environmentally sustainable vacuum treatment with superior uniformity, faster processing times, and no risk of internal oxidation.

Plasma carburizing is commonly used in automotive, aerospace and tooling dies sector. Parts like gears, shafts, bearings, turbine blades, landing gears, and tools and dies. Plasma carburizing is particularly effective for low-carbon steels and medium-carbon steels due to its ability to introduce carbon into the surface layer, creating a hard, wear-resistant outer surface while maintaining the core's toughness and ductility. Steels that

can be carburized are typically low-carbon steels with a carbon content generally between 0.10% and 0.25%.
The goal is to start with a tough, ductile "core" and use the carburizing process to add carbon only to the outer "case" to make it hard and wear-resistant. Steels with higher initial carbon (above 0.40%) are rarely carburized because they become too brittle throughout. For eg. AISI 1020, AISI 8620, AISI 1040, ASI 5120, AISI 9310, AISI 4320, AISI 4140, AISI 4340, 16MnCr5, 20MnCr5, and 18CrNiMo$_6$.

IPR has recently developed an industrial scale plasma carburizing system with gas based quenching which is a first in India. It can carburize up to 500kg load. This system is designed to use acetylene gas which is cheap in nature. Acetylene has stronger carburizing ability compared to methane and propane. Acetylene is chosen as it has a tendency to dissociate when in contact with metallic surfaces only, which allows a uniform carburizing of dense loads, and components with blind holes of small diameters and large lengths while at the same time it almost totally eliminates the soot and tar formation problem known to form from propane. This system is now being is used to develop process recipes for various steels. This system will then be run in a jobshop mode to cater to the needs of the industries.

Figure 1: *Plasma carburizing system installed at FCIPT*

Thermal design optimization of plasma pyrolysis process chamber using CFD analysis

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Among emerging technologies, plasma pyrolysis has gained prominence as an effective alternative to conventional incineration, enabling complete thermal disintegration of waste under oxygen-deficient conditions while ensuring emissions comply with standards set by the Central Pollution Control Board (CPCB) and the Ministry of Environment, Forest and Climate Change (MoEF&CC), India.

Biomedical and other hazardous waste demands robust and scientifically validated plasma processing system to mitigate associated harmful emissions of toxic gases (e.g. dioxins and furans). An important aspect in the development of plasma pyrolysis system is the design of the plasma process chamber herein called as primary chamber which incorporates plasma torches for generating high operating temperatures inside the chamber, typically in the range of 800–1200 ◦C. The uniform thermal distribution is essential for efficient waste disintegration, conversion of organic waste into combustible gases and to suppress recombination reactions that may lead to the formation of toxic species (e.g., PAHs, dioxins, and furans). This temperature limit is also necessary for preventing excessive thermal loading that may cause erosion or melting of the refractory lining. Fig. 1 presents Computer Aided Design (CAD) model of the 200 kg/h plasma pyrolysis system which includes the waste feeder, primary and secondary chamber, conveyor, gas quenching and cleaning system including supporting structures. Systematic strategy was adopted for CFD-driven design and thermal performance analysis of the primary chamber. A transient computational fluid dynamics (CFD) model incorporating radiative heat transfer was developed in ANSYS CFX to simulate the preheating behaviour of primary chamber. In these simulations, no reaction kinetics, chemical species transport were included as the focus of this study is to predict thermal distribution using heat transfer and flow behaviour. At high plasma arc temperatures, radiation is the dominant heat transfer mechanism, while convection and conduction play minor roles. However, including radiation in transient CFD simulations of large plasma chambers is computationally demanding. These computationally intensive analyses were performed on the ANTYA High-Performance Computing (HPC) cluster facility at the IPR, Gandhinagar.

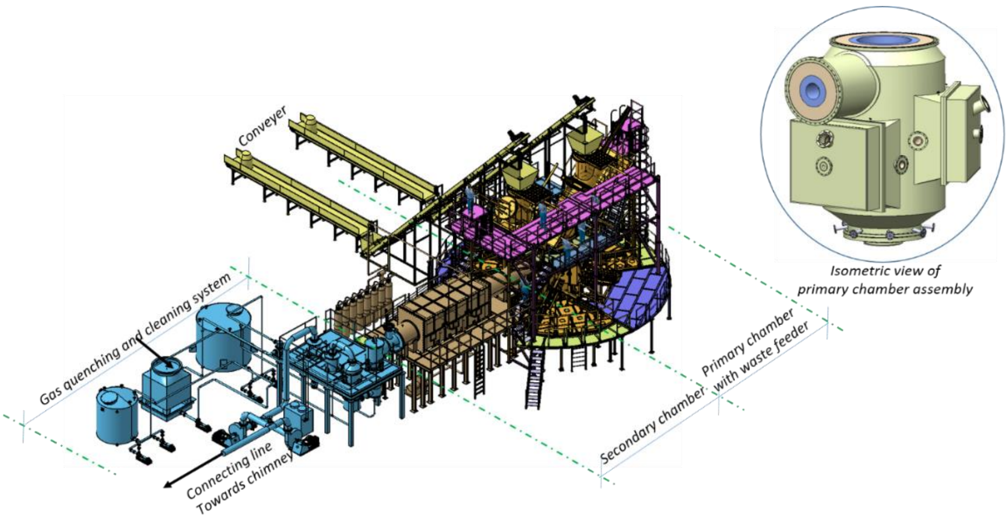
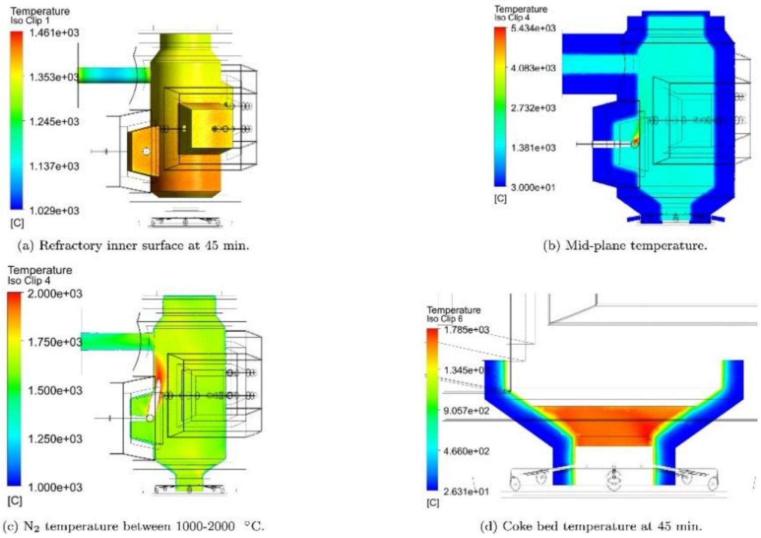


Figure 1: *CAD Model of 200 kg/h Plasma Pyrolysis System*

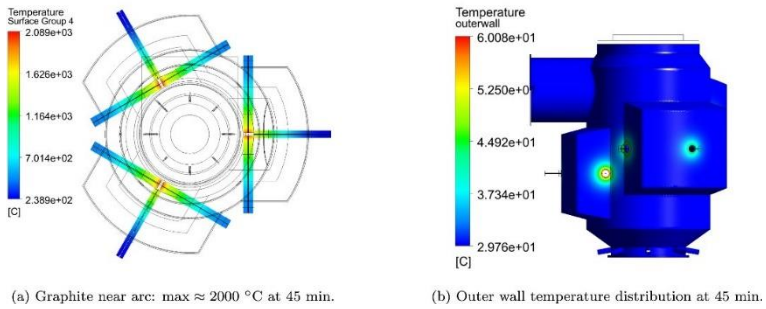
In the first stage, CFD predictions were verified against experimental preheating temperature data for a 50 kg/h experimental set-up of plasma pyrolysis system [1], which validated the methodology. The numerical predictions showed good agreement with experimental data, with deviations within 10–15%. The next stage focused on improving the thermal insulation design of the 50 kg/hr primary chamber, where thermal insulation materials were optimized to reduce heat losses and minimize preheating time. Design improvements, particularly in selection of thermal insulation materials, reduced the preheating duration from approximately 4 hours to 2 hours and eliminated localized hotspots on the outer shell.

Leveraging this validated model, the study was extended for development of primary chamber design of a 200 kg/h plasma pyrolysis system intended for a Common Biomedical Waste Treatment Facility (CBWTF). Multiple design iterations were systematically evaluated for parameters like preheating time, temperature distribution and hotspot formation [2, 3]. The final configuration incorporating three plasma torches, a coke bed, and optimized thermal insulation layering successfully achieved uniform temperatures of ~ 1000 °C within 40-45 minutes, maintained outer wall temperatures below 60 °C, and retained nearly 90% of the supplied thermal energy within the refractory and coke bed. The simulation results of optimized variant are shown in Fig 2 and 3 respectively.



(a) Refractory inner surface at 45 min. (b) Mid-plane temperature. (c) N_2 temperature between 1000-2000 °C. (d) Coke bed temperature at 45 min.

Figure 2: *Simulation results of optimized variant*



(a) Graphite near arc: max ≈ 2000 °C at 45 min. (b) Outer wall temperature distribution at 45 min.

Figure 3: *Graphite and Outer wall temperature of optimized variant*

The results further demonstrate that effective temperature control can be achieved by controlling plasma power or by switching the torches on and off. CFD-based design and analysis of the primary chamber, supported by experimental validation, provides reliable insights into thermal performance and system optimization. The successful scale-up to 200 kg/h plasma system highlights its practical applicability, improving efficiency, reducing heat losses, and enhancing waste treatment process.

References:

[1] Deepak Sharma, Atik Mistry, Hardik Mistry, Paritosh Chaudhuri, P.V Murugan, S. Patnaik, Aadam Sanghariyat, Vishal Jain, Shashank Chaturvedi, S.K. Nema, “Thermal performance analysis and experimental validation of primary chamber of plasma pyrolysis system during preheating stage using CFD analysis in ANSYS CFX” Thermal Science and Engineering Progress 18 (2020)100525.

[2] Deepak Sharma, Atik Mistry, Vadivel Murugan Palanichamy, Adam Sanghariyat, Hardik Mistry, Paritosh Chaudhuri, Shashank Chaturvedi And Sudhir K. Nema. “Design and analysis of a plasma chamber for thermal processing applications” Plasma and Fusion Research 17 (2022) 2406051.

[3] Deepak Sharma, Atikkumar Mistry, Adam Sanghariyat, P. Chaudhuri and S.K.Nema. “Design and CFD driven preheating thermal performance analysis of the primary chamber of plasma pyrolysis plant for biomedical waste disposal: From experimental validation to 200 kg/h scale-up” Energy Conversion and Management 356 (2026) 121310.

Conference Participations

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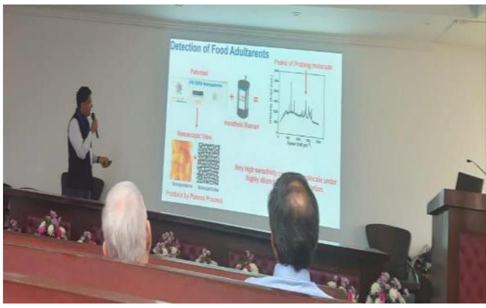
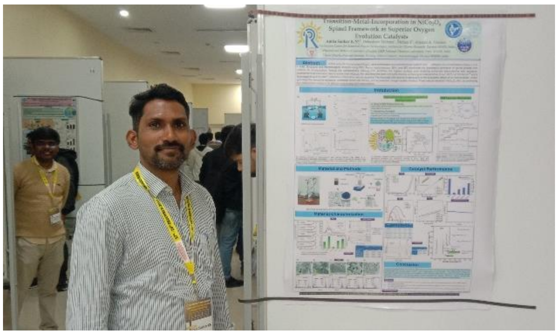
1. Dr. Mukesh Ranjan gave a keynote lecture about “**Plasmonic metal nanoparticles arrays for SERS application**” in the International Conference on Hybrid Materials: Foundation to Frontiers (ICHM 2026) organized by Graphic Era University, Dehradun in collaboration with National Physical Laboratory (NPL), CSIR, New Delhi.



2. Dr. Kamalakkannan (IPR Postdoc Fellow) participated in the *National Conference on Advanced Materials for Energy, Environment and Health*, organized by *The New College, Chennai*, and sponsored by *IGCAR*, Kalpakkam held on 7 January 2026. He delivered an oral presentation titled **“Positron Annihilation and Raman Studies of N^+-implanted 4H-Silicon Carbide.”** The presentation was awarded **Best Oral Presentation**, in recognition of the scientific quality and impact of the work.

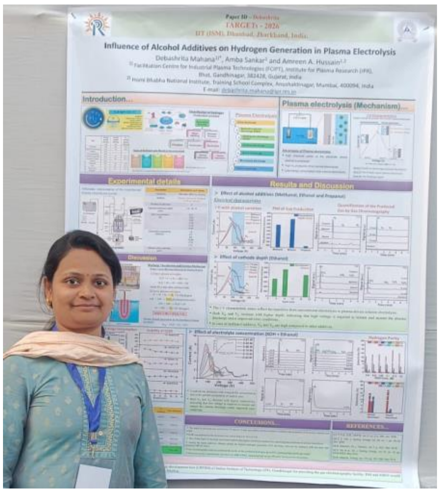
3. Dr. Mukesh Ranjan gave an invited talk about “**Low energy ion surface modification for water harvesting**” at International Conference-cum-Round Table on Translational Research and Innovation in Beam Technologies (ICTRIBT-2026), scheduled from 13–15 February 2026, organized by Central University of Himachal Pradesh, Dharamshala.

4. Dr. Mukesh Ranjan gave an invited talk about “**Sequential growth of metal nanoparticles on low energy ion produced ripple patterns for the isotropic plasmonic response and SERS**” at ***International Conference on Photonics and Emerging Materials for Futuristic Technology (PEMFT-2025)***”, organized by the Department of Physics at the Chaudhary Charan Singh University (CCSU), Meerut, Uttar Pradesh, India, from November 12 to 15, 2025.



5. Dr. Amba Sankar K N presented a poster titled “**Transition-Metal-Incorporation in $NiCo_2O_4$ Spinel Framework as Superior Oxygen Evolution Catalysts**” at the 36^{th} AGM OF MRSI & 7^{th} Indian Materials Conclave and International Conference on Emerging Materials (MRSI-ICEM) 2025 17-20 December 2025, NISER Bhubaneswar, Odisha, INDIA.

6. Dr. Ipsita Chinya, gave an oral presentation on “**Influence of physicochemical characteristics of LLDPE/LDPE Blend packaging films through 40 kHz sub-atmospheric air-plasma treatment**”, at International Conference on Innovations in Materials Science and Technology (ICIMST-2026), 13-14 March, 2026,organizing by Maharashtra Institute of Technology, Chhatrapati Sambhajinagar, India in association with Department of Rubber Technology, Tripura University, Agartala, India and Indian Plastics Institute, Mumbai, India.



7. Dr. Debashrita Mahana presented a poster titled “**Influence of Alcohol Additives on Hydrogen Generation in Plasma Electrolysis**” at the International conference on Trends and Advances in Reforming Green Energy Technologies (TARGETs) 2026, February 13-15 2026, organized by Department of Physics, Indian Institute of Technology (Indian School of Mines), Dhanbad in Association with the Department of Energy Science and Engineering (DESE), IIT Delhi.

8. Atikkumar Mistry participated in Non-Destructive Examination of Process Chamber of Plasma Pyrolysis Plant., 1st Annual Conference & Exhibition on Non-Destructive Testing and Supporting Technologies (NDT Expo 2026), “The Capitol – The Forum Celebration & Conventions, Club 07”, Forum Street, Shela, Ahmedabad, Gujarat, March 01-02, 2026.

9. Dr. Vivek Pachchigar (Ex FCIPT/IPR PhD student) and currently a Podtdoc fellow at University of Illinois Urbana-ChampaignU.S.A working for a Fusion Startup gave a talk about “**Understanding Plasma-Material Interaction: From Fusion to Materials Processing** ”. Dr. Mukesh Ranjan (Innovation Ambassador) introduced the speaker. Dr. Vivek talked about how the fusion start-up exploring other substitute materials like Ti and Deuterium plasma effect on its surface. This will be a cheaper option then W. In the end he talked about various future possibility in fusion start-ups for the PhD students. In the end there was a very fruitful discussion.

Journal Publications & IPR Research /Technical Reports

[1] Role of surface modification and defect formation on resistive switching behaviour of BiFeO3 based heterostructure by dense electronic excitation
Hajra Sumana, Rathod Urjitsinh I., Karavadra Devanshi, Ranjan Mukesh, Solanki Vanaraj, Sahoo Jayaprakash, Yadav Sajaan, Vagadia Megha, Meena Ramcharan Ojha, Sunil Katba, Savan, Ravalia Ashish
ACS Applied Electronic Materials (**2026**).

[2] Temperature-dependent dielectric relaxation and Raman phonon correlation in melaminium glycolate hemihydrate
S. Akshay Kalyan, K. Kamalakkannan, Mukesh Ranjan, N. Kanagathara
The European Physical Journal B (**2026**)99.

[3] Synergistic Effects of Thermal Arc Plasma Processing and Magnetic Field Tuning on Mixed – Phase Iron Oxide Nanoparticles
Savita Pannu, Subrat Kumar Das, Partha Halder, Prachi B Orpe, Satya Prakash Reddy Kandada, Balasubramanian C
Applied Physics A (**2026**) 132.

[4] Effect of Hexamethyldisilazane (HMDS) coupling agent on SiO_2 nano-powder for oil/water separation application
Janki Shah, Vivek Pachchigar, Rohit Sharma, Mukesh Ranjan
Silicon **(2025).**

[5] ***Sequential growth of Ag nanoparticles on ripple-patterned Si: Insights from GISAXS/GIWAXS***
Tarundeep Kaur Lamba, Tejasva Vashistha, Sharanjeet Singh, K.P. Sooraj, Sebin Augustine, Raghavan Ranganathan, Sarathlal Koyiloth Vayalil, Dileep Kumar, Mukesh Ranjan
Physica B: Condensed Matter (**2025**).

[6] Luminescence signature of deep level defects evaluation in N + semi-insulating 6H- SiC
K. Kamalakkannan, R. Rajaraman, K. Sivaji, Mukesh Ranjan
Materials Letters 404 (**2026**) 139616.

[7] Tunable Titanium and Tantalum oxide coatings as highly efficient antibacterial agents
Kartikey Chaturvedi, Mittireddi Ravi Teja, Mayank Dotiyal, Deepak G. Prajapati, Radhe Shyam, Mukesh Ranjan, Emila Panda,
Ceramic International **(2025).**

[8] Swift heavy ions irradiation studies on transport and impedance spectroscopic properties of $La_{0.5}Gd_{0.2}Ca_{0.3}MnO_3$ thin films
Apexa Maru, Indrajitsinh Bihola, Bharavi Hirpara, Sagar Sen, Tarundeep Kaur Lamba, Mukesh Ranjan, M. R. Gonal, P. S. Solanki, N. A. Shah & Keval Gadani
Journal of Materials Science: Materials in Electronics 36 (**2025**) 2002,

[9] Design and CFD driven preheating thermal performance analysis of the primary chamber of plasma pyrolysis plant for biomedical waste disposal: From experimental validation to 200 kg/h scale-up
Deepak Sharma, Atikkumar Mistry, Adam Sanghariyat, Paritosh Chaudhuri, S.K. Nema
Energy Conversion and Management 356 (**2026**) 121310.

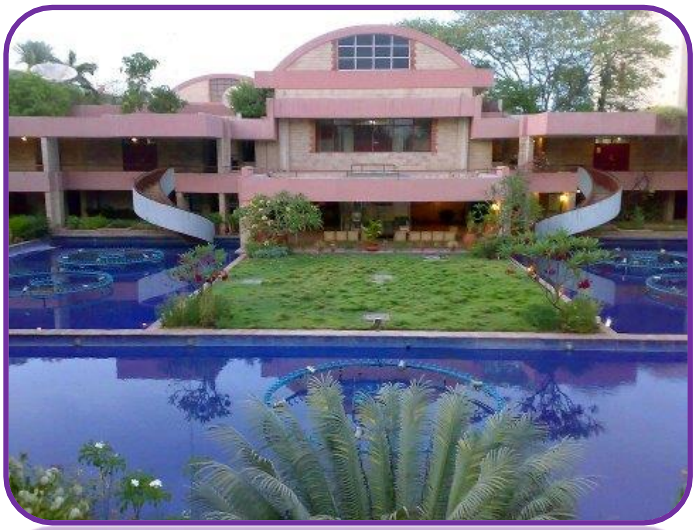
AIC-PLASMATECH

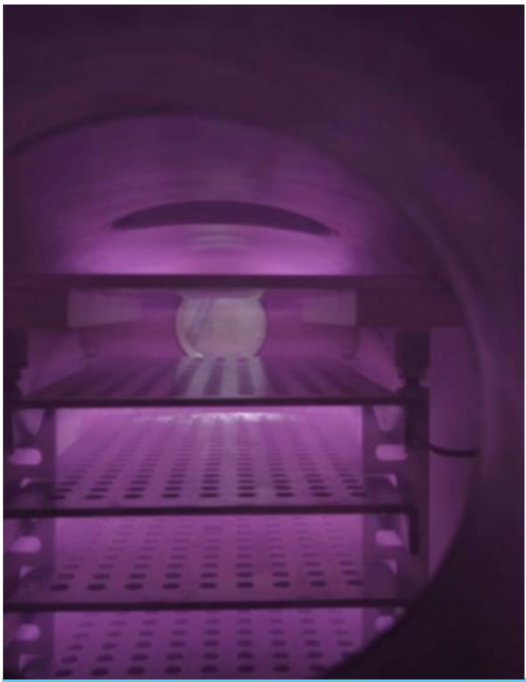
The Department of Atomic Energy (DAE), through its units and aided institutes, has been transferring and deploying several advanced technologies for the betterment of society. In support of the Government of India's initiatives on Atma Nirbhar Bharat and Start-up India, the DAE proactively launched incubation centres at BARC Mumbai, IGCAR Kalpakkam, RRCAT Indore, IPR Gandhinagar, and VECC Kolkata. This step aims to make the expertise, sophisticated infrastructure, and technologies of DAE available to industries and society at large. Additionally, the DAE initiated the recognition of such incubation centres with the Atal Innovation Mission, NITI Aayog, New Delhi, as 'Atal Incubation Centres'.

Based on this initiative, the Institute for Plasma Research established an Atal Incubation Centre as a special purpose vehicle under Section 8 of the Companies Act 2013 in December 2023, with 100% ownership by DAE. The Atal Incubation Centre, is popularly known as 'AIC-Plasmatech' and 'Plasmatech Innovation Foundation'.

AIC-PLASMATECH OFFER

The Atal Incubation Centre (AIC Plasmatech) offers not only office space to startups but also essential mentoring by IPR's scientists, along with access to cutting-edge technologies and infrastructure. Additionally, it provides business mentoring from experts and external mentors, as well as support in areas such as intellectual property/patenting, marketing, and branding.





Industrial Scale Plasma Etching System

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