COVER PAGE

Project Title: Resonant Microwave Plasma Sources to Improve the Efficiency of Compact Plasma-Based Accelerators	
Federal Award Identification Number: DE-SC0025743	
Agency Code: 8900	**Organization:** Office of High Energy Physics
Recipient Award Identification Number: 208314	**Project Period:** 01/01/2025 - 12/31/2027
Reporting Period: 01/01/2025 - 12/31/2025	**Budget Period:** 01/01/2025 - 12/31/2025
Report Term: Once per Budget Period	**Submission Date and Time:** 11/06/2025 11:30 AM ET
Principal Investigator Information: Prof. Abbas Semnani	**Recipient Organization:** The University of Toledo 2801 W. Bancroft St., MS 944 Toledo, OH 43606-3390 Country: USA **UEI:** XA77NAJYELF1

ACCOMPLISHMENTS

- What are the major goals and objectives of this project?
  The overarching goal of this effort is to investigate the fundamental principles and develop efficient cold plasma line sources specifically tailored for compact laser-plasma accelerators.
- What was accomplished towards these goals?
  - What was the technical approach? Using high-Q microwave resonators to confine electromagnetic energy within a specific volume where plasma generation is desired. Specifically, we plan to use anapole dielectric and evanescent-mode cavity resonators to develop energy-efficient and high-density plasma line sources, tailored for laser-plasma acceleration.
  - Describe progress toward completion of major activities or significant objectives identified in your proposal and include significant results, key outcomes, and other achievements. We have developed and fully characterized a 2-cm plasma line with energy transfer efficiency exceeding 90% and electron density higher than 1e16 cm-3, using our DR anapole resonator technology. We are in the process of extending this technique to a 5 cm line and already have successful design and simulations. The final goal will be a 10-cm plasma line, This goal will be pursued in two parallel ways: (1) making a larger (lower frequency) resonator with a 10-cm slot, or (2) cascading two 5-cm plasma lines.
  - As the project progresses, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.
- What do you plan to do during the next reporting period to accomplish the goals and objectives? Fabrication and experimental characterization of our 5-cm plasma line, both in atmospheric pressure and vacuum conditions. Design and simulation toward development a 10-cm line, and how we can have more uniform and high (~1e17 cm-3) plasma density all over the line.
- What opportunities for training and professional development were provided for participants? A research faculty, a phD student, and an undergradute researcher are involved in this project. The plan is to add another PhD student to be involved from Spring 2026 semester.
- How have the results been disseminated to communities of interest? In particular, provide details for any dissemination not reported in the research product section of this report. The 2-cm plasma line paper in under review in IEEE Transactions on plasma science. We also presented the results in 2025 IEEE APS/URSI conference to the electromagnetic community showing how microwave resonators can be used for other applications like plasma sources, and in 2025 APS GEC conference to the plasma community. The PI also had a few invited seminars, including those at the Ohio State University and the University of Michigan, where the results of this effort have also been reported to the audience.

PRODUCTS

The products shown below include only Publications with a 'Published' status and Intellectual Properties with a 'Granted' status. Products with other statuses are not included in this report. The Revision Type indicates whether a product is New (newly added), Updated (existing product modified), or No Change (existing product reported without modifications) during the current budget period. Note that 'Updated' statuses may appear more frequently as products progress through the publishing process. All products listed have been reported for the current project period of this award.

PUBLICATIONS

There are no publications to report.

INTELLECTUAL PROPERTIES

There are no intellectual properties to report.

PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

The table below only contains participants who have identified an affiliation with the Awardee Institution. Participants from any associated subawards may not be included in this count.

PARTICIPANTS DETAIL

Project Role	Number of People	Total Person Months Worked
Faculty	1	6
Graduate Student (Research Assistant)	1	12
Principal Investigator/Project Director	1	3
Undergraduate Student	1	6
Total Responses	**4**	**27**

PARTNERS DETAIL

There are no partners to report.

IMPACT

- What was the impact on the development of the principal discipline(s) of the project? As an applied electromagnetics expert, this project provided a great opportunity for the PI to explore a new and very important field of science in particle accelerators. One of the main thrusts of the PI research is using high-Q resonators to generate energy-efficient plasma sources, and this is a great opportunity to also expand these plasma sources toward particle acceleration needs.
- What was the impact on other disciplines? High quality plasma sources are building blocks of modern laser-plasma accelerators. So, the main objective is to develop plasma sources specifically tailored for acceleration applications. However, the developed techniques can also be extended toward energy-efficient plasma sources for many yother emerging applications such as surface treatment, roll-to-roll amterial processing, propulsion, PFAS and microplastic removal, and ag and food industries. The PI already has several collaborations in some of these fields.
- What was the impact on physical, institutional, and information resources that form infrastructure? The PI is the founding director of the Adaptive Radiofrequency and Plasma Lab (ARPL). This is the only electromagnetic and plasma lab at the University of Toledo, which is also being used for educational and outreach activities. With the support of this project, we could aquire an ICCD camera for high-resolution and temporal imaging of our plasmas which is a great added capability to our lab, for our general plasma diagnostic uses.
- What was the impact on technology transfer?
    - Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use. Our technology in making highly efficient plasma jets using microwave resonators, specifically DR anapole and evanescent-mode cavity resonators, have been patented and have received much attention by external companies working on various applications of plasma, from propulsion, to surface treatment and bio-medicine. We are actively working with these companies to answer their questions and optimizing our plasma sources for their specific needs.
    - Include transfer of results to entities in government or industry, instances where the research has led to the initiation of a start-up company, and adoption of new practices. We have tow patents on our resonant microwave plasma techniques, as listed below. However, they have not been licensed yet although we have active discussions with several companies in this regard.
      P1- A. Semnani and K. S. Kabir, "Power-efficient microwave plasma jet based on evanescent-mode cavity technology," US Patent, US2023/0178868A1, 2023.
      P2- A. Semnani and M. R. Akram, "A power-efficient microwave plasma jet based on a dielectric anapole structure," US Patent, US2025/0311081A1, 2025.
- What was the impact on society beyond science and technology? By developing energy efficient plasma sources, those can be used in many other applications beside accelerators, including material processing, propulsion, bio-medicine, PFAs and microplastice removal, as well as food and agricultural applications. We always have visitors in our lab, ranging from elementary students to high schoolers and their families, as well as from various industries. Demostrating this technology always grasp much attention as we can generate stable plasma with the same density that many other technologies need several times more power to do.
- What was the impact on the development of human resources? One research faculty, one PhD student, and two undergraduate students have been involved in this project. For the second year, the plan is to add another PhD student to become involved from Spring 2026. The results and lab demo of the developed plasma sources are continously being used to make our visitors aware of the importance of the research and make more of them enthusiastic about STEM.
- What percentage of the award's budget was spent in foreign country(ies)? There was just one international travel by the PI to attend the APS GEC 2026 in Seoul, South Korea. This is one of the major conferences for plasma community, specificall those interested in gaseous electronics, in which the PI presented three major research on the group including one on resonant microwave plasma technology.