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A DISCHARGE PLASMA SOURCE DEVELOPMENT PLATFORM FOR ACCELERATORS: THE ADVANCE LAB AT DESY

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Abstract

Novel plasma-based accelerators, as well as advanced, high-gradient beam-manipulation techniques—for example passive or active plasma lenses—require reliable and well-characterized plasma sources, each optimized for their individual task. A very efficient and proven way of producing plasmas for these applications is by directly discharging an electrical current through a confined gas volume. To host the development of such discharge-based plasma sources for advanced accelerators, the ATHENA Discharge deVelopment ANd Characterization Experiment (ADVANCE) laboratory has been established at DESY. In this contribution we introduce the laboratory, give a summary of available infrastructure and diagnostics, as well as a brief overview of current and planned scientific goals.

INTRODUCTION

Plasma-wakefield accelerators could hold the key to revolutionising future particle accelerator facilities by significantly shrinking their footprint through the use of GV/m plasma-based accelerating stages [1–3]. In a typical discharge-ionised plasma source [4–6], a neutral gas confined within a solid structure is ionised by a high-voltage current pulse. Control of the spatial and temporal plasma profile can be realised by careful design of the structure confining the material, tuning of the current pulse properties and detailed knowledge of the evolution of the plasma. Figure 1 shows the geometry of a typical discharge plasma source used as an accelerating stage in a beam-driven plasma-wakefield experiment. In this mode, discharge plasma sources have several important applications in accelerator and photon science:

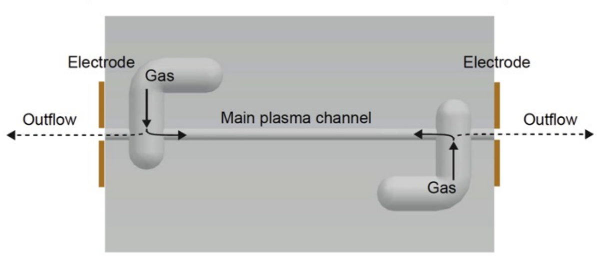

Figure 1: Schematic of a typical discharge plasma source used at DESY. The central channel and gas inlets (opposite ends of the main channel) have a circular cross-section and are milled from sapphire. The exits of the main channel are open to allow the passage of charged particles beams and lasers. Electrodes with the same diameter opening are placed around these exits.

- Accelerating stages, supporting GV/m accelerating gradients
- Waveguides, focusing EM radiation over multiple Rayleigh lengths
- Active plasma lenses (APL), producing radially uniform kT/m magnetic field gradients for charged particle focusing

The concept of accelerating and focusing charged particles using centimetre-scale plasma devices has already routinely demonstrated plasma acceleration, laser guiding and focusing of charged particles in APLs, all at repetition rates of 1 to 10 Hz [7–9]. However, this must be boosted into the multi-kHz continuous wave or MHz burst regime in a stable and reliable way in order to compete with the integrated-luminosity demands of the next generation of plasma-based photon science and particle physics facilities.

THE ADVANCE LAB

The ADVANCE (ATHENA Discharge plasma deVelopment ANd Characterization Experiments) lab was commissioned at DESY, Hamburg in order to facilitate the next steps in discharge plasma source development. The laboratory consists of several key features:

- Highly flexible vacuum chamber with modular outer panels, capable of hosting multiple plasma sources or long cells up to 1 m in length.
- Multiple, high repetition-rate high-voltage current pulse modulator systems
- Multiple plasma diagnostics including optical emission spectroscopy and two-color laser interferometry
- Auxiliary diagnostics such as synchronised, GHz-resolution signal readout and processing of current pulses and material temperature.
- A Ti:Sa laser with 1 kHz repetition rate, 35 fs, 3 mJ and an average power of 3 W
- On-site plasma source design and production.

Figure 2 shows a plasma source in operation at the ADVANCE lab. Multiple gas species can be used ranging from hydrogen to heavier gases such as argon. An ambient vacuum pressure of 1×10^{-7} mbar can be maintained without continuous gas flow and with continuous gas flow an ambient pressure of 1×10^{-3} mbar.

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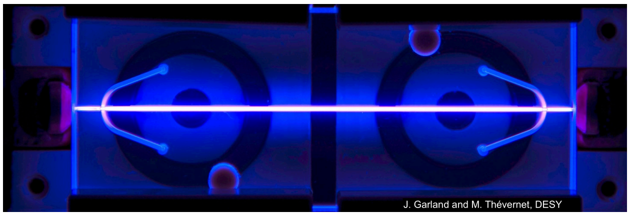

Figure 2: Image of a plasma generation event in a discharge plasma source in the ADVANCE lab, DESY.

PLASMA DIAGNOSTICS

Central to the plasma source design, development and characterisation capabilities in the ADVANCE lab are the plasma diagnostics. Two main types of plasma diagnostic are being commissioned: optical emission spectroscopy and two-color laser interferometry.

Optical Emission Spectroscopy

An optical emission spectrometer (OES) setup was commissioned, capable of measuring spatially and temporally resolved plasma density and temperature. The design was based on previous experimental setups at DESY [10] but has an improved resolvable plasma density range of 5×10^{14} to 1×10^{19} cm^{-3}. New light collection optics enable 2 ns time resolution and sub-mm longitudinal resolution. A radial plasma profile measurement system is currently under development. At present, the diagnostic relies on doping the target gas with a small percentage of hydrogen and exploiting the strong pressure-broadening effect of the optical alpha emission line in the hydrogen-Balmer series.

Figure 3 shows the spatially and temporally resolved plasma density evolution as measured by the OES in the ADVANCE lab. A comprehensive understanding of the plasma profile evolution is of critical importance in most plasma source applications and hence forms a critical part of the laboratory's capability. A plasma temperature diagnostic based on emission line intensities is also under development, utilizing the OES setup to its full potential.

Two-color Longitudinal Laser Interferometry

A two-color longitudinal laser interferometer was previously developed at DESY [10, 11] and is presently being commissioned in the ADVANCE lab. This diagnostic provides a rapid, robust method of measuring the line-of-sight averaged plasma density of any plasma species. The resolvable plasma density depends on the length of the plasma column within the source and the sensitivity is presently 2×10^{15} cm^{-2}. The temporal resolution so far achieved was of the order 10 ns. Future developments include wavelength doubling techniques to access lower density regimes. Figure 4 shows an example of the average plasma density measured in different plasma sources at DESY.

Auxiliary Diagnostics

The current pulse can be measured with a 2.5 GHz ADC system, allowing high-resolution current-trace retrieval and

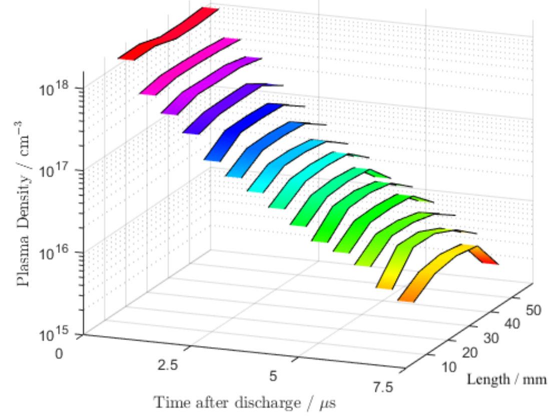

Figure 3: Temporally and spatially resolved plasma density measurement in a 50 mm long discharge plasma source in the ADVANCE lab.

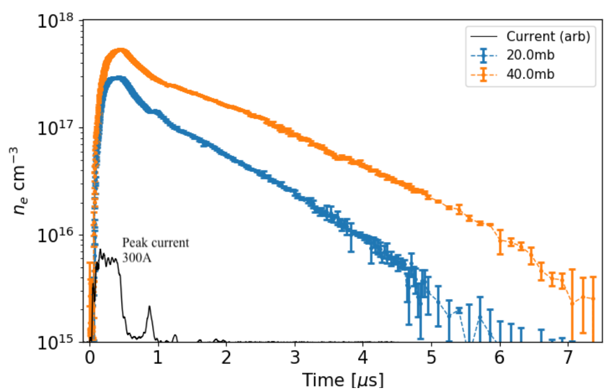

Figure 4: Temporally resolved plasma density evolution in a discharge plasma source of length 33 mm and diameter 1.5 mm. Backing pressures of 20 mbar and 40 mbar argon are indicated respectively but the in-cell pressure a factor of around 7 lower [10].

facilitating accurate jitter analysis. Figure 5 shows a typical current profile measurement in the ADVANCE lab.

Device temperature diagnostics are presently being commissioned and will allow the temperature of plasma cell components to be assessed, such as the sapphire cell, copper electrodes and holder body. Thermocouples and infrared camera technology will be employed to realise this. Fast-intensified cameras are already in operation in the OES diagnostic and will be used for the laser interferometry diagnostic. Additional fast-intensified cameras will be used in laser-spot diagnostics and other plasma imaging techniques.

HIGH VOLTAGE MODULATOR DEVELOPMENT

Several high voltage (HV) pulse modulators have been set up to support the various requirements of breakdown voltage, current amplitude, and repetition rate imposed by

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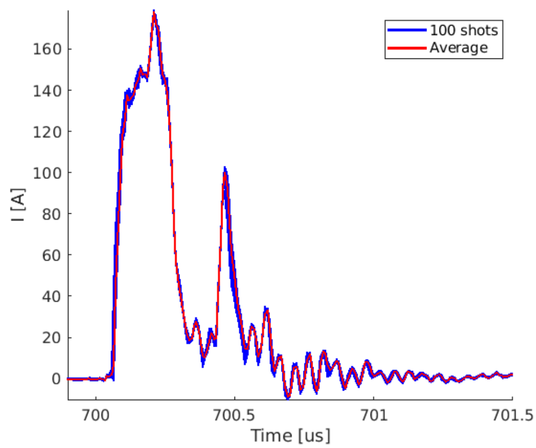

Figure 5: High-voltage current pulse profile measured on the high-voltage electrode side.

the different operational scenarios of the investigated discharge sources. For low voltage applications, a 10 Hz, < 3 kV thyristor pulser with peak currents exceeding 1 kA at pulse lengths of ca. 1 μs is employed. The work-horse modulators for capillary discharge development and operation at DESY so far have been cable pulsers with thyratron switches, which supply capillary discharge plasma sources with HV pulses in the following parameter ranges:

- voltage: 1 kV – 28 kV
- peak current: < 1.2 kA
- pulse lengths: 200 ns – 800 ns
- typical repetition rate: 10 Hz.

Even though a 2 kHz burst operation of these pulsers has been recently established , additional modulators based on semiconductor switches are being commissioned to increase the accessible operational ranges. One of these modulators is designed to deliver bursts of HV pulses at MHz repetition rate to enable studies of plasma sources and lenses for accelerators with similar bunch train structures. Modulators with multi-kHz, continuous-wave capabilities are also being set up and feature variable pulse lengths as well as independent tuning of pulse voltage and peak current.

SCIENTIFIC GOALS AND OUTLOOK

The ADVANCE lab was recently brought online and is currently being commissioned. The laboratory will facilitate a comprehensive scientific road map in several key development areas:

- High repetition-rate plasma sources
- Next-generation EM radiation guiding
- Active plasma lenses for high-gradient beam focusing
- Plasma source stability and reliability
- Diagnostics and tool development
- Measurement/theory plasma characterization benchmarking
- plasma-wakefield accelerator R&D at DESY.

This road-map aims to drive forward the development of plasma sources at this new high-repetition-rate frontier and to act as a comprehensive test bed for both new and existing plasma sources, placing it at the centre of plasma-wakefield R&D at DESY and beyond.

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