Development of stable plasma cells with high discharge rates at DESY's ADVANCE Lab

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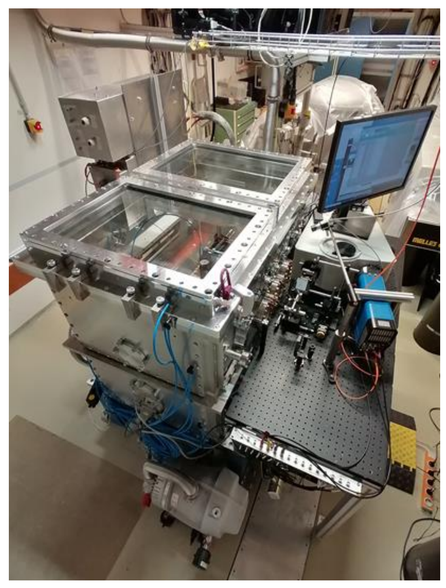
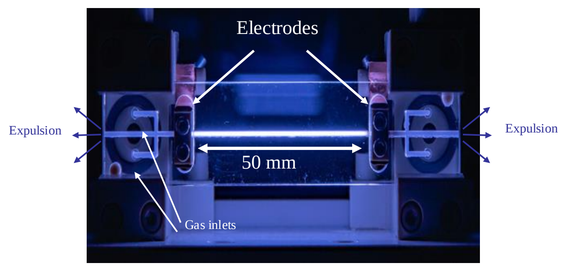
ADVANCE Lab

1. Lab overview

A critical component in generating and manipulating high-energy beams in plasma-wakefield accelerators is a reliable, well-characterized, and optimized plasma source with high discharge rates and stability. To meet these requirements, the **A**THENA **D**ischarge De**v**elopment **an**d **C**haracterization **E**xperiment (**ADVANCE**) laboratory has been established at DESY. The lab's mission is to develop advanced plasma cells for use in particle acceleration, as well as for other potential applications in research and industry. This contribution reports on the latest developments and activities at the ADVANCE lab, including the implementation of high-repetition-rate discharges, and the introduction of a new 500-mm long cell utilizing a combined glow- and arc-discharge setup and virtual-electrode concept.



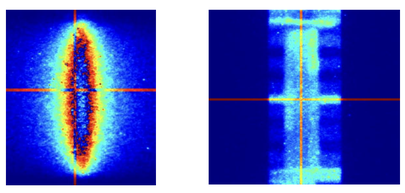
- Cable pulsers with thyratron switch:
  - voltage: 1 kV – 20 kV
  - peak current: < 1.2 kA
  - pulse lengths: 200 ns – 800 ns
  - typical repetition rate: 10 Hz
- Discharge capillaries made of sapphire:
  - Filled with Argon or Hydrogen
  - Accelerating stages, GV/m accelerating gradients
  - Active plasma lenses radially uniform with kT/m magnetic field gradients for particle focusing



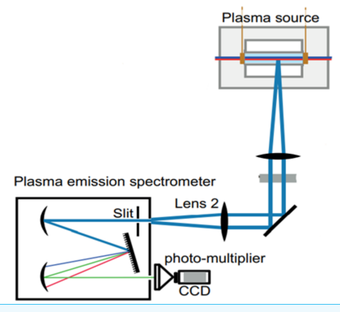
Main diagnostics:

- Plasma density and temperature measurements
  - Optical emission spectroscopy (OES):
    Hydrogen alpha and beta lines at Balmer series; resolvable plasma density: 5×10^{14} to 1×10^{19} cm^{-3} 2-ns time resolution and sub-mm longitudinal resolution
  - Two color interferometry (TCI):
    Ti:Sa laser: 1 kHz repetition rate, 50 fs, 1 mJ, average power 1 W sensitivity of 2 $\times10^{15}$ cm^{-2} temporal resolution of the order 10 ns.
- Cell, electrode and holder temperature
  - Interferometry, Pt sensors, and Infrared cameras
- current pulse measured with a 2.5 GHz ADCs

J.M. Garland *et al.*, "A Discharge Plasma Source Development Platform for Accelerators: The ADVANCE Lab at DESY", in *Proc. IPAC'22*,, pp. 1886-1888.



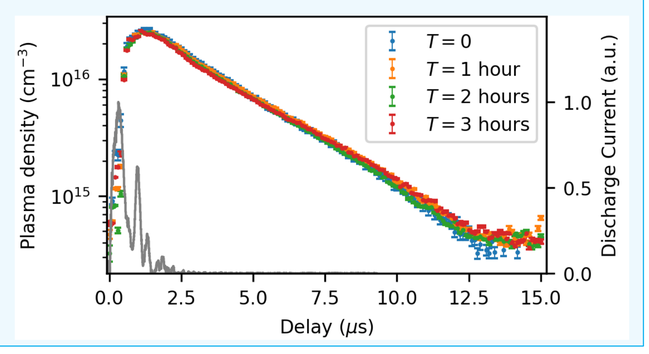
OES setup and example images



Long-time discharge tests

Plasma (500-mm cell) is reproducible well.

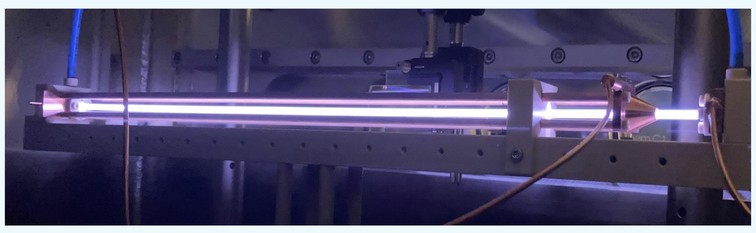
There is no significant change in performance over $\mathcal{O}(10^5)$ discharges at 5 Hz discharge rate (180000 shots in an hour) , and 20 kV



2. Plasma target for high overall efficient acceleration

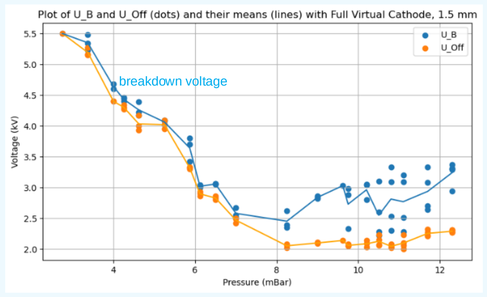
New 500 mm sapphire tube designed, tested and characterized:

- Glow discharge → pre-ionisation
- Virtual electrode (an electrode with no direct contact to plasma) → limits DC voltage needed to form glow discharge, enhances electric field hence field emission at cathode
- Half-meter length cell → ~ 500 MeV energy gain at ~1 GV/m → high efficient acceleration → **see L. Boulton's poster**

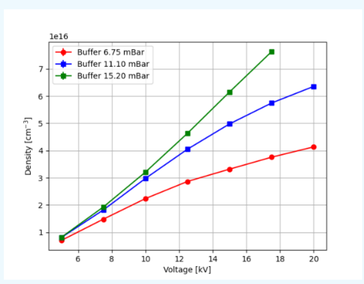


Example cell characterization studies

Glow discharge breakdown studies
to find most stable working point

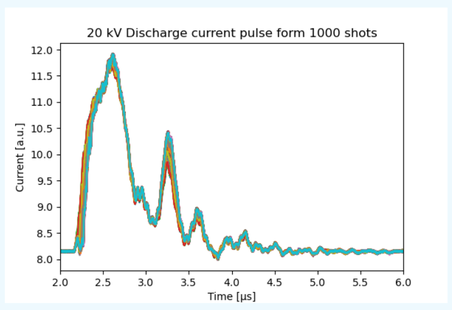


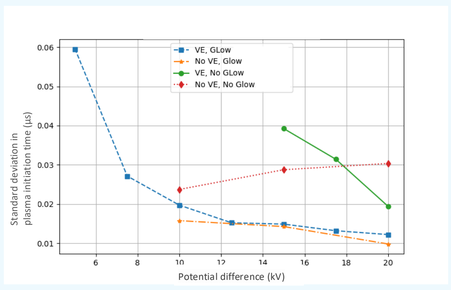
Glow discharge 3.8 kV
Voltage and pressure scan



Discharge timing jitter over 1000 shots

To study the stability of plasma, 1000 successive shots with discharge rate of 2 Hz were studied by recording the images from spectrometer and the currents measured by using Pearson coils and ADCs. The studies were done by varying several parameters such as, the gas flow rate/buffer pressure, glow discharge voltage, cable pulser discharge, removing and adding the virtual electrode, and applying HV in reversed polarity.





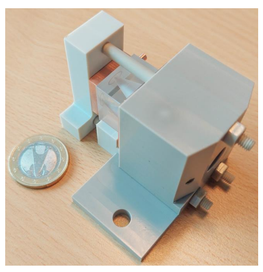
Preliminary results indicate a reduction in discharge time jitter by combined DC and pulsed discharges. The formation of arc discharge (by applying 20 kV from cable pulser) is expected to be more reproducible, having a plasma (with a density of about 10^4 cm^{-3}) already been established from randomly available free charge carriers in the cell.

The behavior and analysis of plasma density jitter is more complex and needs more detailed studies.

Preliminary analysis of jitter estimation for typical working points :

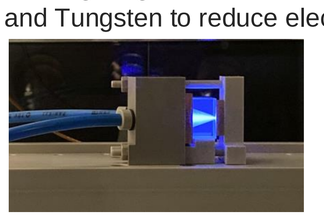
Buffer pressure (mBar)	Glow voltage (kV)	Pulser voltage (kV)	Time Jitter (ns)	Density (1/cm³)	Density jitter (1/cm³)	ratio
12	3.2	20	12	0.82e16	1.54e14	1.88 %
6	3.8	20	30	1.07e16	5.01e14	4.70 %
8	3.2	15	25	1.08e16	1.91e14	1.77 %
8	3.2	20	25	1.04e16	2.36e14	2.27 %

3. Positron lens for International Linear Collider (ILC)



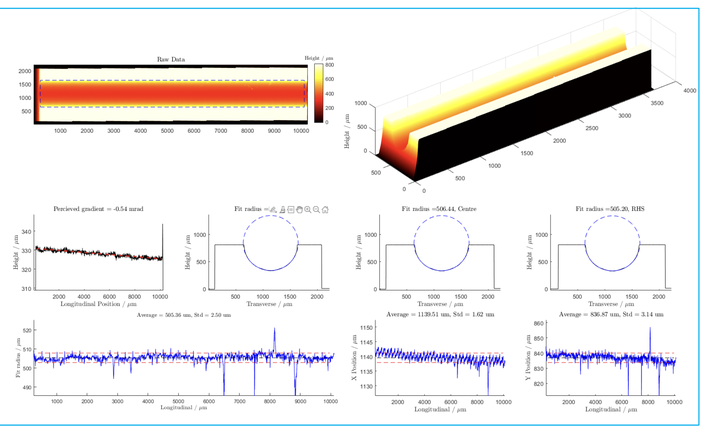
- Downscaled prototype version of a tapered plasma lens used for positron matching at ILC
- Cone-shape structure to captures highly divergent positrons with large energy spread and focus directly onto the beam axis, and for decreasing the magnetic field along cell
- Bunch spacing 554 ns ~ MHz

- Succecfull plasma generation
- High temporal/spatial resolution studies of plasma discharge with fast cameras
- Investigating different materials e.g. Copper and Tungsten to reduce electrode erosion



4. Capillary cell longevity tests

kHz repetition rate targets must be durable for at least hours-days of operation, corresponding to 30M shots.
We have performed tests showing that the capillaries survive 2M shots, as characterized via confocal microscopy.
A surface roughness of up to 3 µm has been measured after discharges with up to 100 Hz repetition rate.

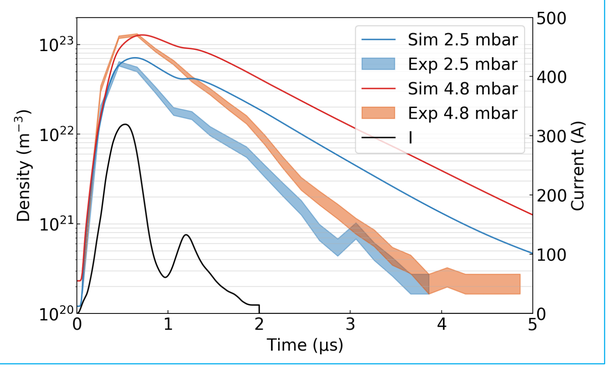


6. Plasma parameter simulation

- COMSOL Multiphysics, hydrodynamic model approach
- 320 A, 400 ns current pulse in 50 mm x 0.75 mm capillary
- Radially symmetric, longitudinally mirrored simulations
- Electron density measured by OES
- Hydrogen gas with two gas filling pressures

- Further simulation on plasma temperature and heat load on capillary walls undergoing for better cooling of the cell.

preliminary benchmark



6. Outlook

- Cell temperature measurements, simulation and cell cooling design and studies
- Further longevity tests
- Characterization of plasma parameter using further plasma diagnostic techniques including TCI
- Further analysis and simulation of the long plasma cell with variation of the position of the virtual electrode etc.

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