# An inductively coupled plasma discharge for laboratory astrophysics

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LABORATORY FOR PLASMA TECHNOLOGY

## Summary

We designed and evaluated a first-of-its-kind plasma discharge for the FIREBALL IV experiment at CERN's HiRadMat facility [1]. The 3-meter-long inductively coupled radio-frequency (RF) plasma is created with 5 kW electrical power at 13.56 MHz through two helical coils connected in series. This is an update from the design used in the FIREBALL I and II campaigns [2]. A stable discharge with electron densities exceeding $1 \times 10^{18}\,\mathrm{m}^{-3}$ was achieved. Subsequently, a parameter sweep was conducted to find optimal operation conditions. The FIREBALL campaigns study plasma instabilities as a relativistic electron-positron beam [3] travels through the plasma and is a laboratory experiment in astrophysics [4].

## Experimental setup

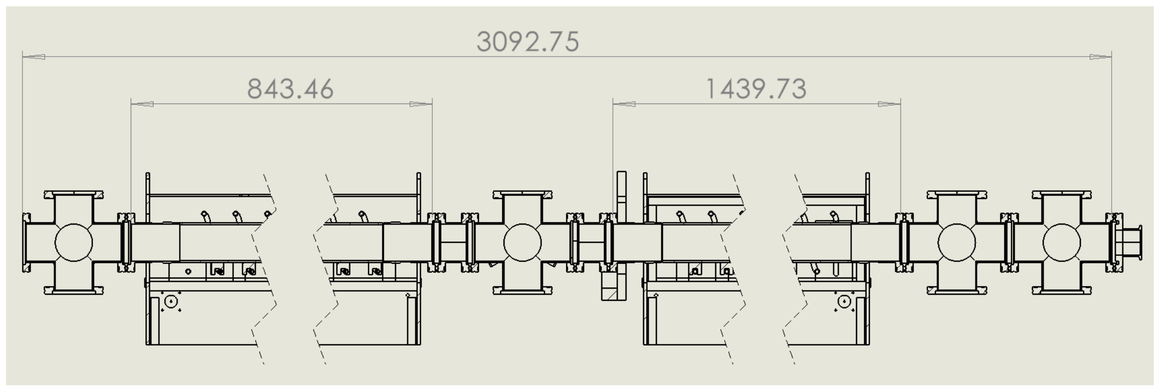



**Figure 1:** CAD drawing of the plasma cell assembly. The plasma cell is composed of two glass tubes, each placed inside a solenoid (the primary coil) through which RF current is applied. The glass tubes are connected by a cross piece, which also serves as access for diagnostics, including a double Langmuir probe.

| Parameter | Coil 1 | Coil 2 |
|---|---|---|
| Number of windings | 13 | 24.2 |
| Length [mm] | 663 | 1234 |
| Pitch [mm] | 51 | 51 |
| Coil diameter [mm] | 93 | 93 |
| Copper tubing [mm] | 6x1 | 6x1 |
| Glass inner D [mm] | 58 | 58 |

The new coil design was adapted to the existing plasma cell that was used in FIREBALL III. This entailed the separation of the single electrical coil into two parts, the design of two Faraday cages and a shielded electrical connection between both coils to mitigate RF interference. Studies on the pitch of the coils and needed cable lengths for tuning were conducted.

## Electrical circuit and devices

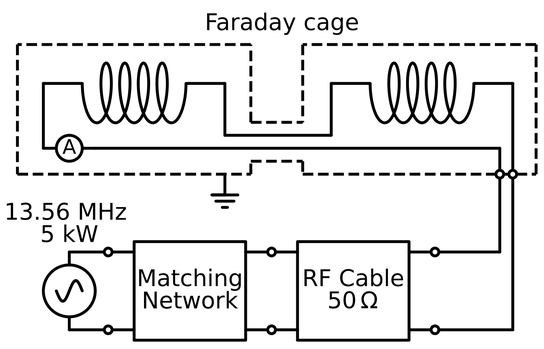



**Figure 2:** Electrical circuit of the FIREBALL IV plasma cell.

**Power supply:** Paramount HF 6013 Generator (6 kW, water-cooled)
**Matching network:** Navio 5 kW
**Cable:** 7/8" HELIFLEX Air-Dielectric and braided copper wire (1 cm width)
**Faraday cage:** Custom-built from aluminium plate and 0.25 mm copper mesh
**Current monitor:** Pearson 110 current transformer

## Langmuir Probe

In the characterisation of the plasma cell and in-situ during the experiment, plasma density measurements were acquired by a double Langmuir probe. The double probe was chosen due to its measurement robustness in RF plasmas. With RF notch filters and floating potential electronics, precise voltage-current characteristics were achieved [5]. In Figure 3 an exemplary curve is shown, measured in the centre cross piece.

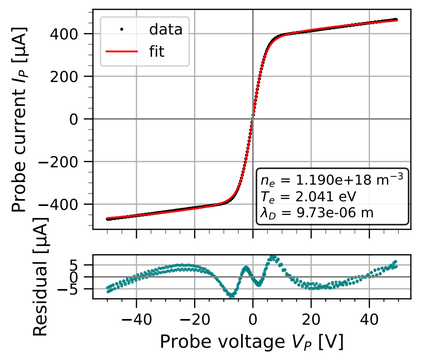



**Figure 3:** Langmuir probe data.

## Pressure sweep

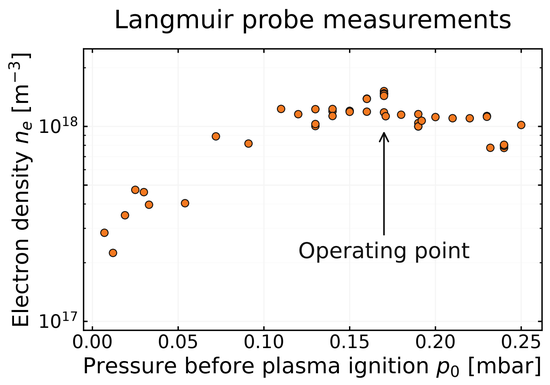



**Figure 4:** The electron density $n_e$ in the middle of the center cross piece versus argon gas pressure.

Electron density was measured for different argon pressures. The measurements were taken inside the middle cross piece and therefore do not reflect the overall discharge density. An operating point was chosen taking into account the electron density, visual homogeneity and the stability of the discharge. This operating point was further characterized using multiple longitudinal density measurements.

## Electron density profile study

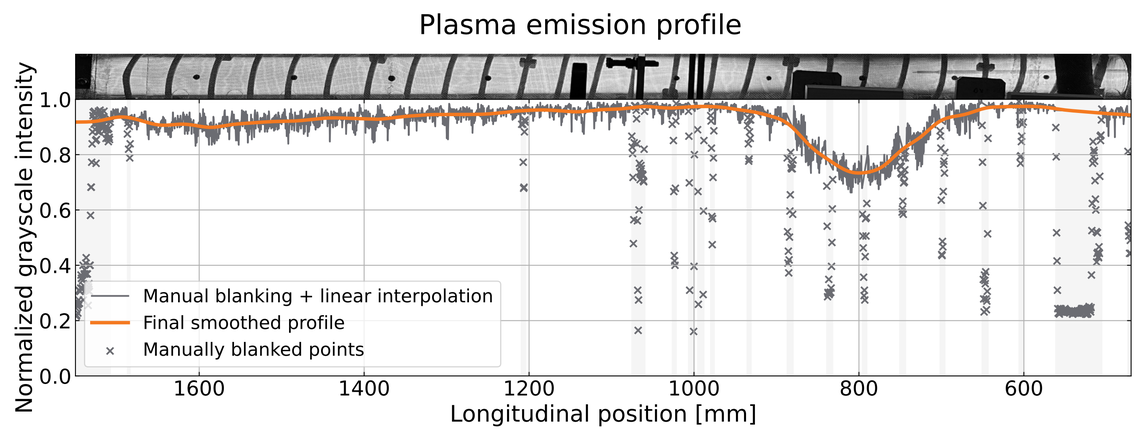
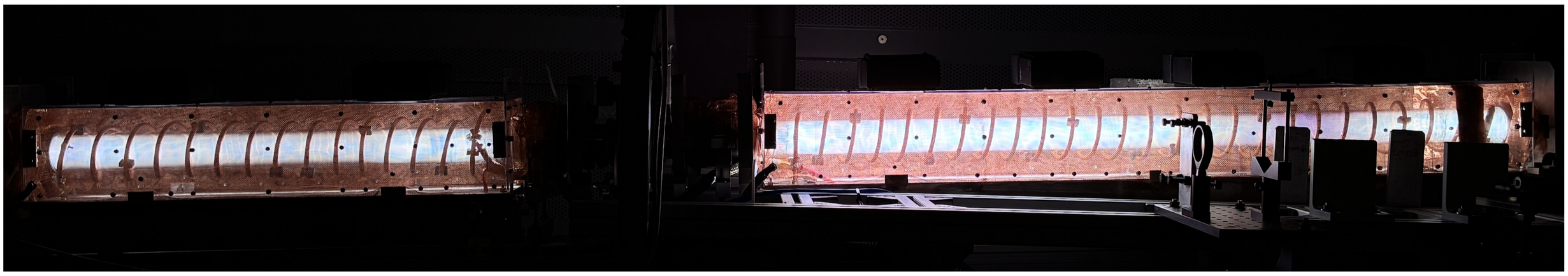



**Figure 5:** Evaluation of optical emission along the downstream plasma cell tube.

## References

[1] C.D. Arrowsmith *et al.*, *Phys. Rev. Res.* **3** (2021) 023103.
[2] C.D. Arrowsmith *et al.*, *Journal of Instrumentation* **18** (2023) P04008.
[3] C.D. Arrowsmith *et al.*, *Nature Communications* **15** (2024) 5029.
[4] C.D. Arrowsmith *et al.*, *Proc. Natl. Acad. Sci.* **122** (2025) e2513365122.
[5] L.J. Beal *et al.*, *Rev. Sci. Instrum.* **83** (2012) 073506.

## Plasma discharge



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FIREBALL