Update on the development of scalable plasma sources at CERN

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Scalable plasma source R&D

- Demonstrate uniformity, scalability and reproducibility within spec.: n_e = 7×10^{14} cm^{-3}/0.25% uniformity

→ Focus on plasma diagnostics with 1 m helicon plasma source (HPS) and 3 m discharge plasma source (DPS)

→ Get inputs from institutes for hardware design/optimization based on simulations and local experiments

→ Build scalable modules at CERN

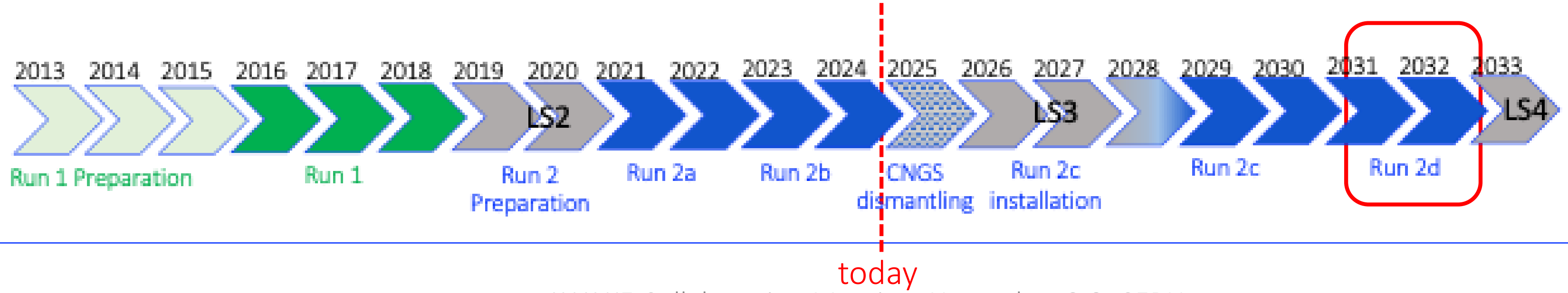
- Milestones:

→ 1st milestone achieved = 10 m DPS test with protons in the AWAKE tunnel "DPS May 2023 Run"

→ End 2024 = First density uniformity profile for both sources

→ End 2025 = Internal review whether scalable technology can already be used for Run 2c

→ Scalable Plasma Source review (around 2027): decision for Run 2d scalable source, procurement and design



HPS 2024 program

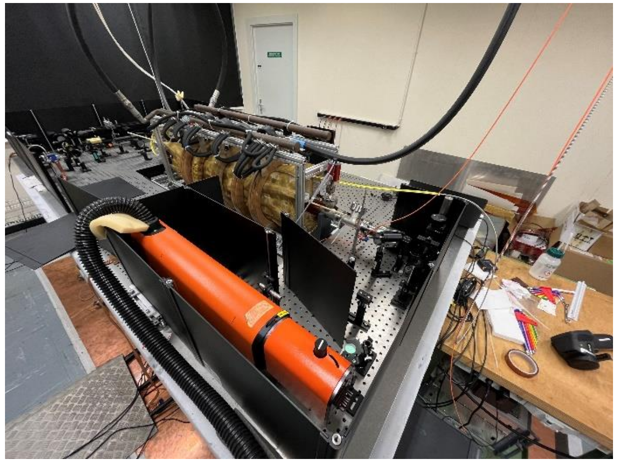
- Hardware upgrades for stable RF-operation (no arcing) and reproducibility (matching, directional couplers) → CERN
- **Diagnostics comparison** to rule out discrepancies between diagnostics (effect of viewport…) → IPP/EPFL/CERN
- **Axial density profile** with two types of RF-antennas to assess plasma uniformity → EPFL/CERN
- Helicon waves simulations and **parameters studies** → Univ. Wisconsin
- Share diagnostic for axial density profile with DPS → EPFL/CERN


2 m MAP setup at Univ. Wisconsin


HPS lab at CERN

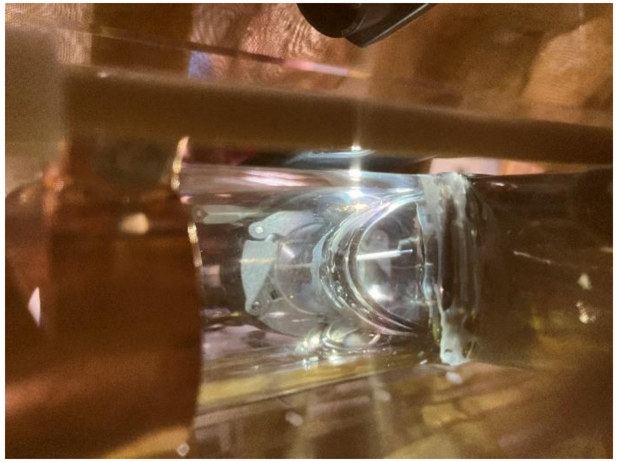
1 m HPS in b.169 lab, Ar 8 Pa, 3x10 kW RF/400 A DC

HPS diagnostics comparison



→ Thomson scattering (TS)

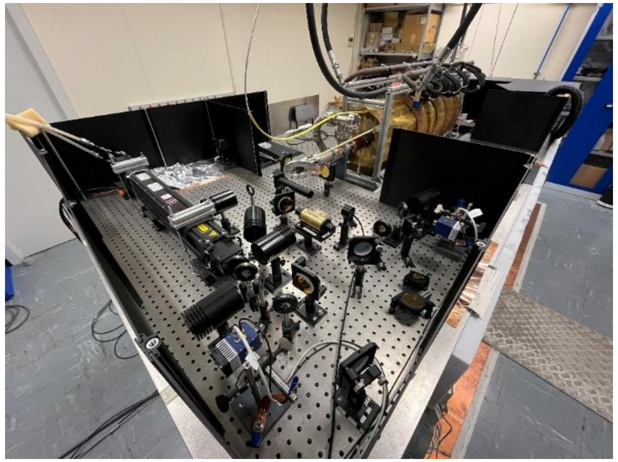
- n_e and T_e measurements
- Local (in space and time)
- Time scan
- Axial profile (moving collection optic)
- Needs absolute calibration
- Needs accumulation of 100's of shots



→ Langmuir probe (LP)

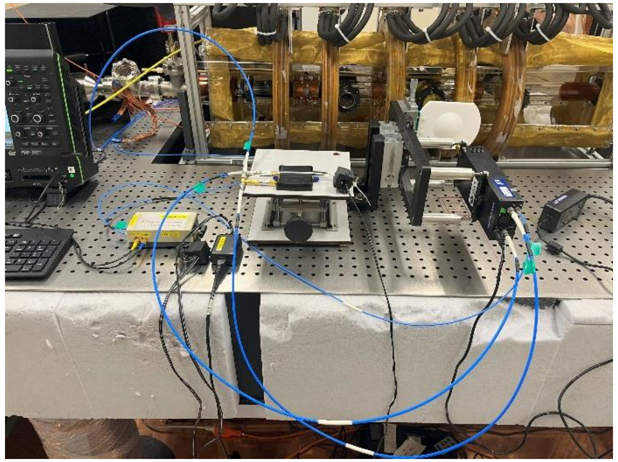
- Plasma/floating potential
- Local
- Time-resolved
- Shot to shot evaluation
- Transverse profile (moving the probe)
- Need fit and model to retrieve n_e

MAX PLANCK INSTITUTE FOR PLASMA PHYSICS



→ CO_2 Interferometer

- Line integrated density
- Time-resolved
- Shot to shot evaluation
- Radial profile (moving the cell)
- Abel inversion to retrieve n_e



→ mm-wave interferometer / cut-off

- Line integrated density
- 100 GHz cut-off → $n_e = 1.24 \times 10^{20}\ m^{-3}$
- Time-resolved
- Shot to shot evaluation
- ~ 10 mm waist at focus!

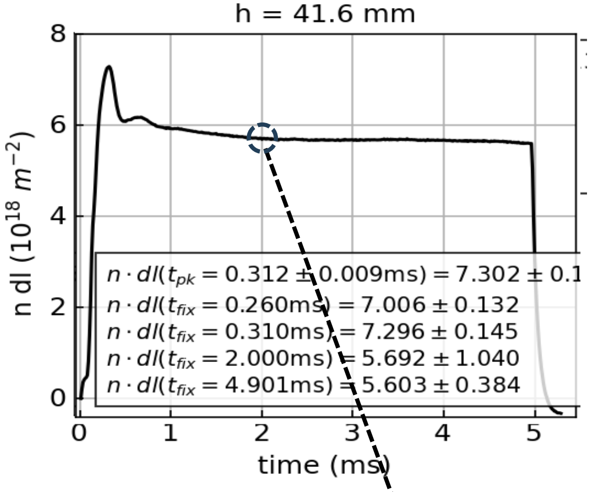
Diagnostic forum: https://indico.cern.ch/event/1395533/

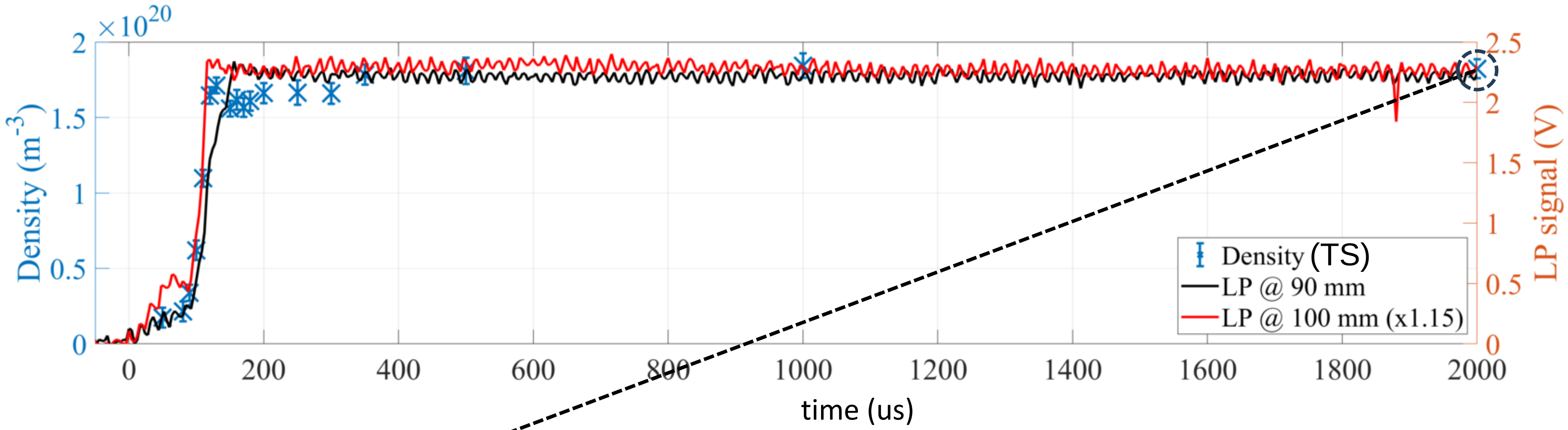
HPS diagnostics comparison → 9kW/350A

→ Langmuir probe shows plasma expansion in the viewport, especially at start of RF-pulse (< 0.5 ms)

→ Line integrated dynamic of CO_2 interferometer at start must be taken with caution (non-axisymmetric)!

→ Focus on "steady state" > 1ms to compare diagnostics





Courtesy Christine Stollberg (EPFL/SPC)

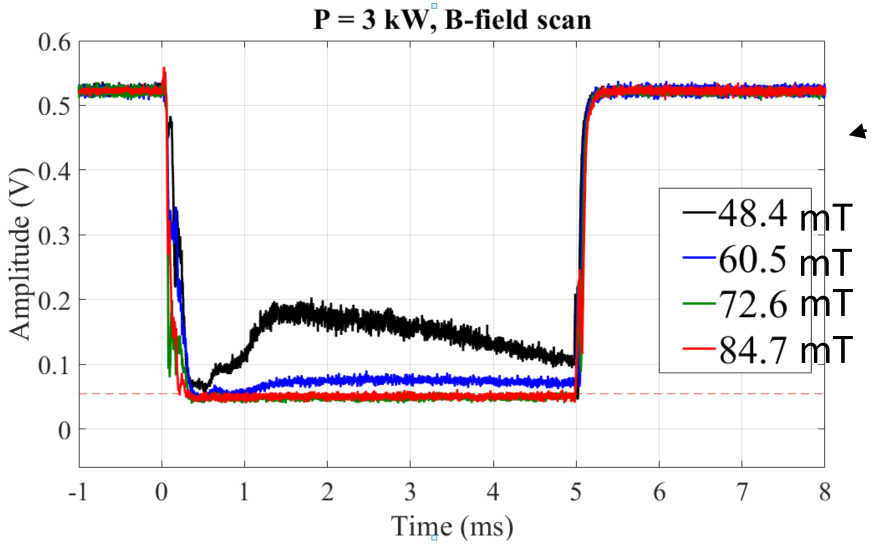
CO2 at 2 ms	TS at 2 ms
5.7e18 m-2	3.9e18 m-2
2.6e20 m-3	**1.8e20 m-3**

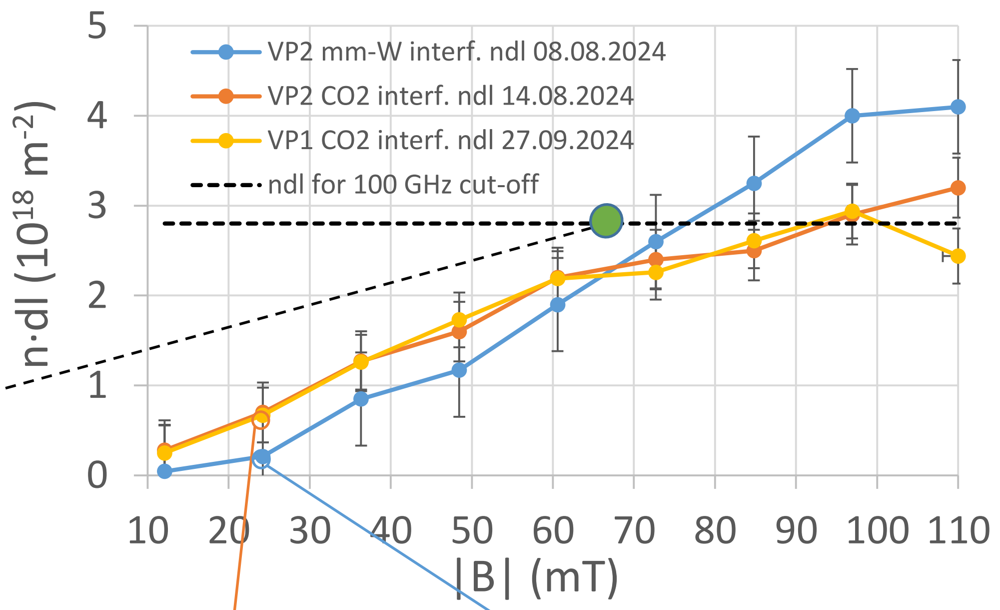
→ 30% discrepancy between CO2 and TS

HPS diagnostics comparison → B-field scan

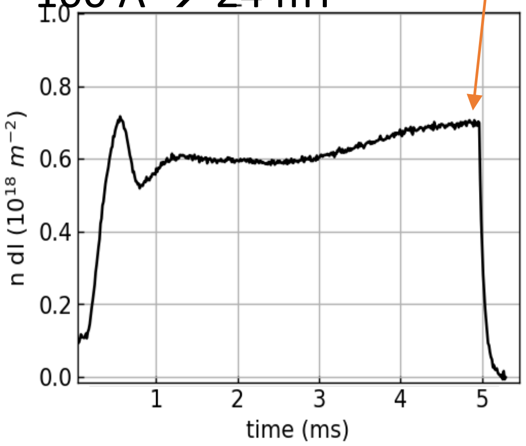
→ Low power (3kW/antenna) B-field scan

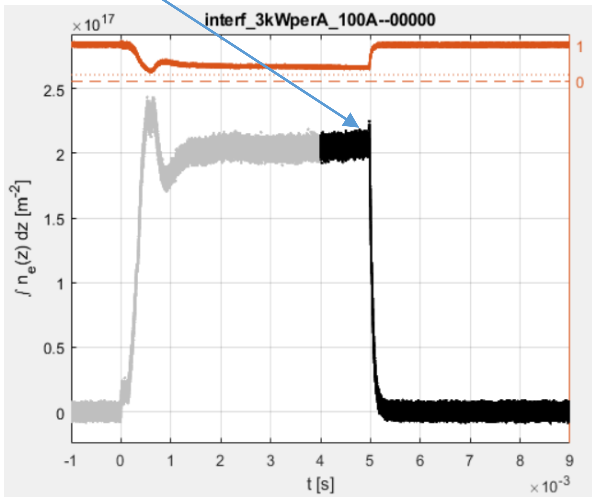
→ qualitative match between mm-wave and CO2 interferometry





100 A → 24 mT

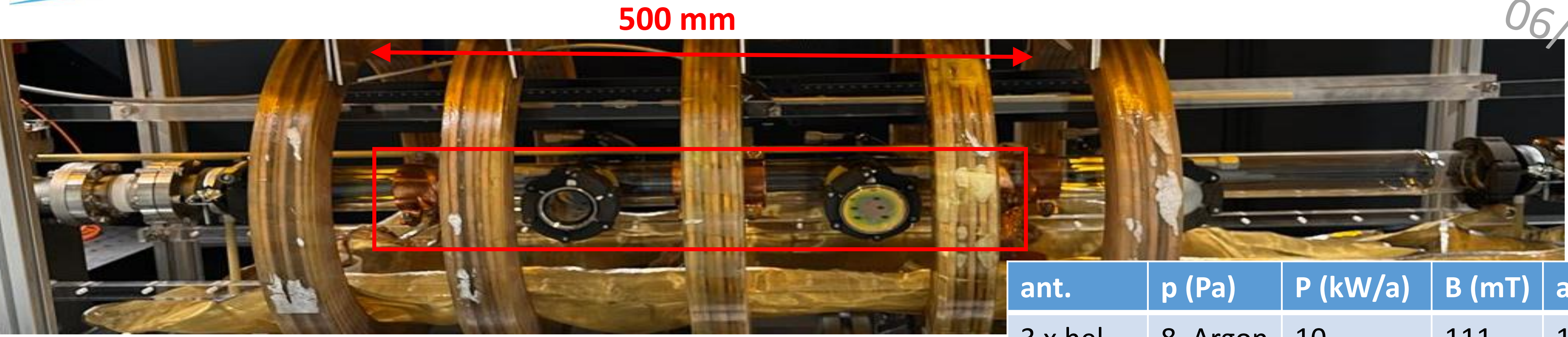




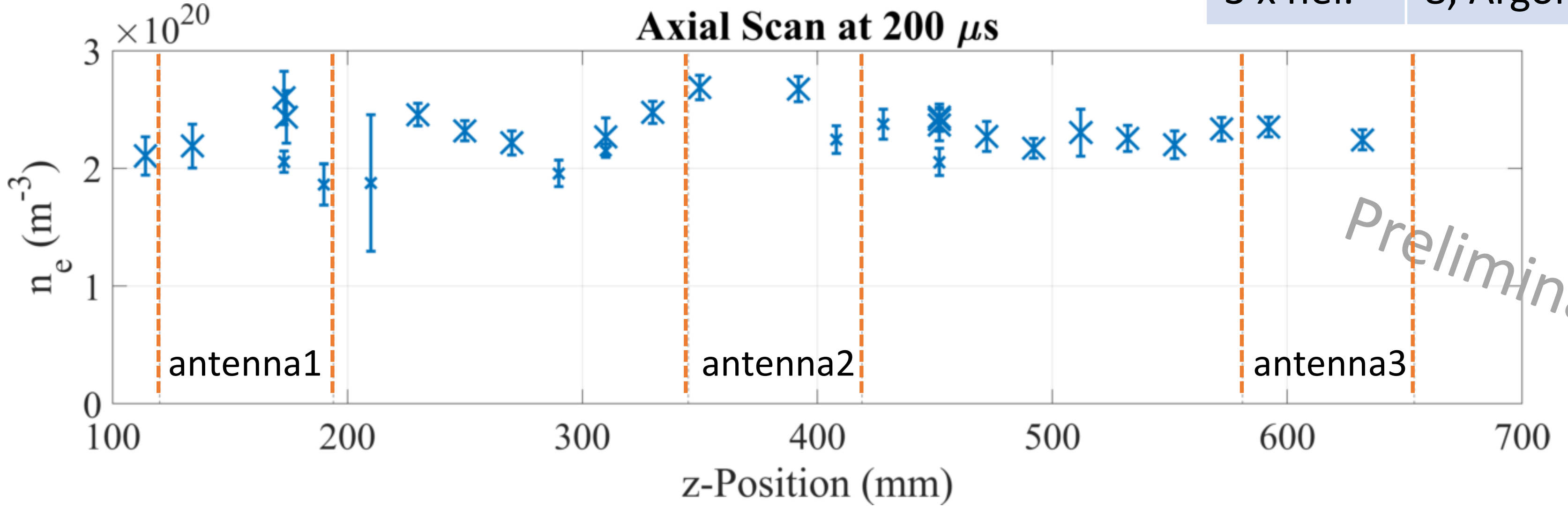
→ mm-wave cut-off occurs between 60 and 70 mT, close to the value identified by line-integrated diagnostics

HPS axial density profile over 500 mm

06/2024



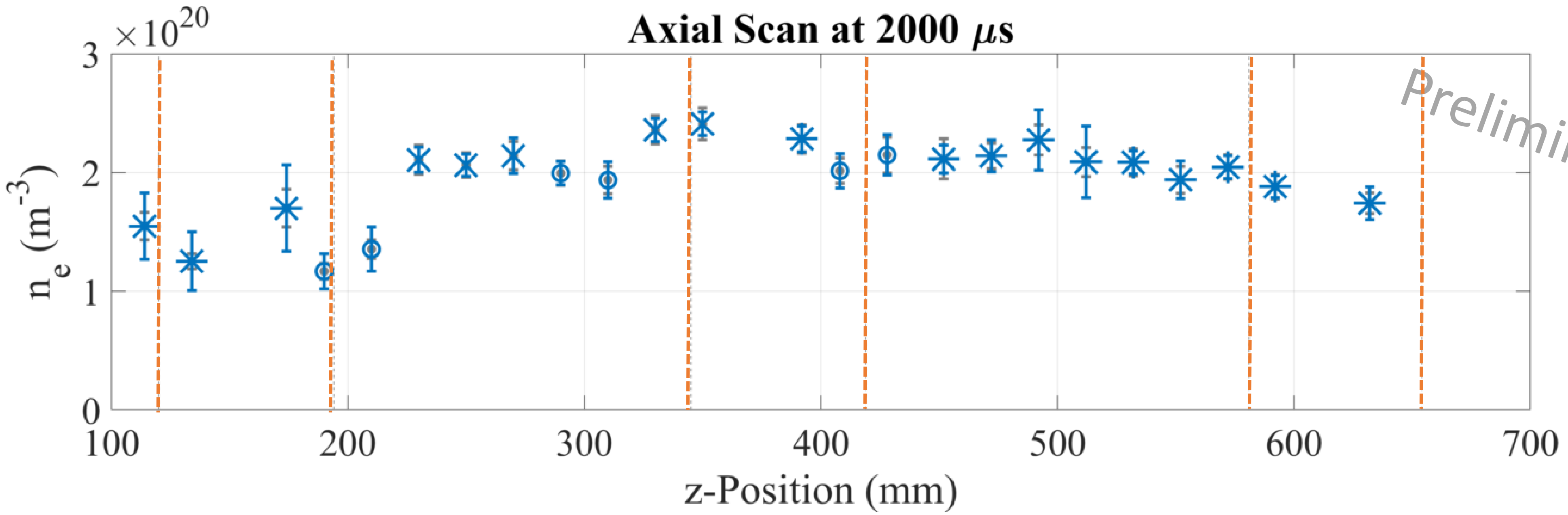
ant.	p (Pa)	P (kW/a)	B (mT)	accum
3 x hel.	8, Argon	10	111	100



Preliminary data

Axial profiles change in time

06/2024



- 2 days for full axial scan:
- At each position: Raman, TS, plasma background, Raman → statistic uncertainty + calibration
- In steady-state, **axial homogeneity ± 6 %** (200 mm – 600 mm), better than expected ☺

→ See Christine's talk: [59th AWAKE Technical Board (20 June 2024) · Indico]

HPS parameters studies

Conclusions

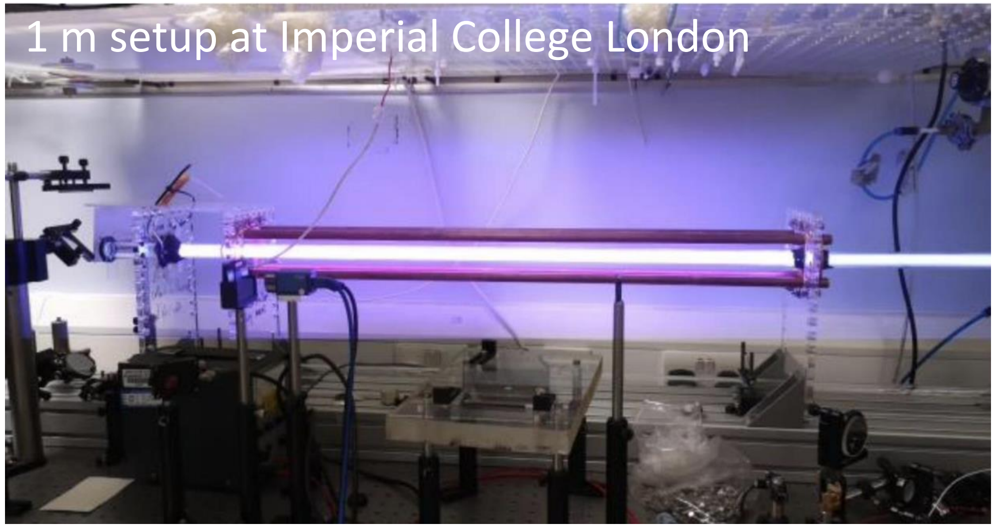
- Next-generation particle accelerators require high density and high axial uniformity
- We have identified actuators to control density profile, as summarized in the table
- We have found a strong link between the fueling of the plasma with neutral argon and the resultant density profile

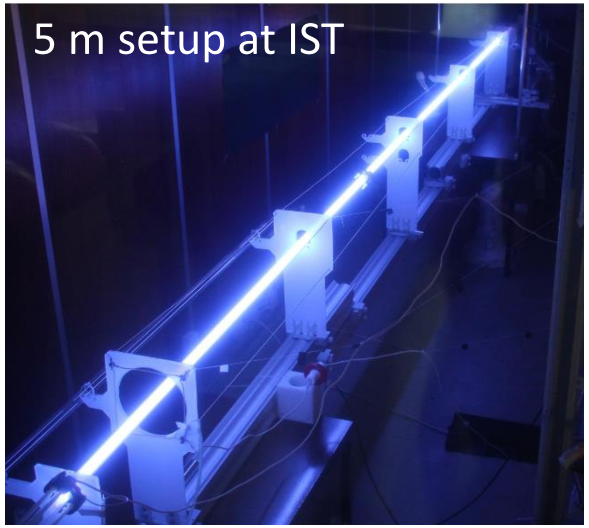
Parameter	Effect
Chamber diameter	Radial fueling dominates in small-diameter chamber; axial fueling dominates in large-diameter chamber.
Number of Antennas	Two-antenna n profile is linear superposition of one-antenna profiles.
Neutral Flow	Low $v_i - v_n$ leads to more uniform profile with no neutral flow.
Pressure	Tradeoff between density and homogeneity.
Power	Density increases with power with little effect on homogeneity (1 – 2 kW)

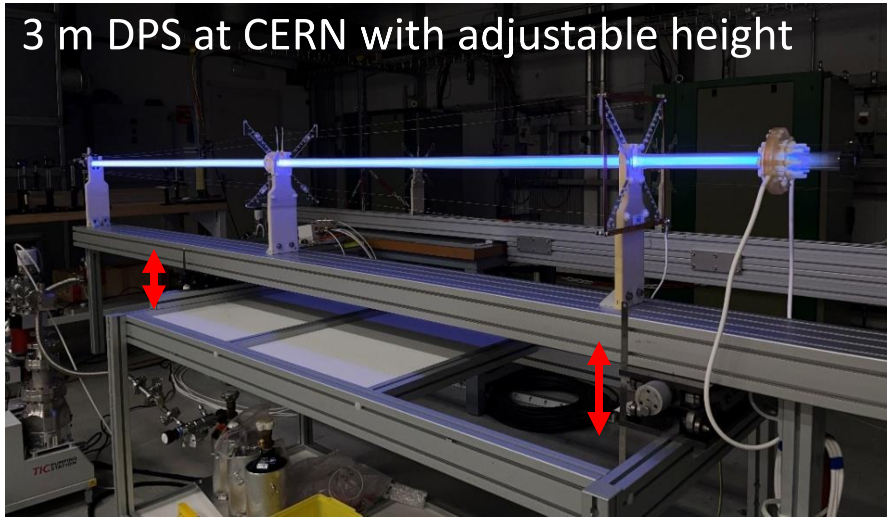
→ Michael Zepp, PhD defence 1st November 2024, see details here: https://indico.cern.ch/event/1466944/

DPS 2024 program

- **Transverse interferometry** diagnostic development, OES and new pulse generators → Imperial College
- **Parameters scans** (pressure/current/repetition rate) + statistics to assess stability and reproducibility → CERN/IST
- **Plasma electrical characterization** and smaller diameter tube studies (higher ionization fraction) → IST
- Build and commissioning of a 3 m DPS to benchmark with 10 m source and prepare for Thomson Scattering → CERN
- **Radial density profile with 3 m DPS** using interferometry (longitudinally average) → CERN
- Thomson scattering to assess axial density uniformity of 3 m DPS → EPFL/CERN



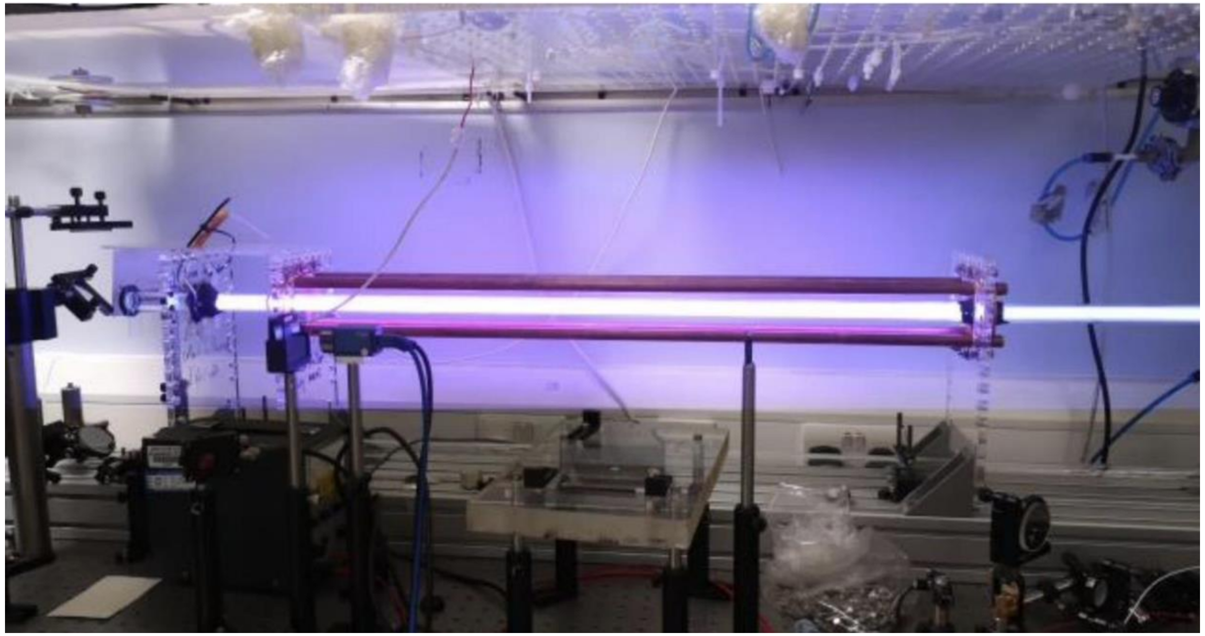




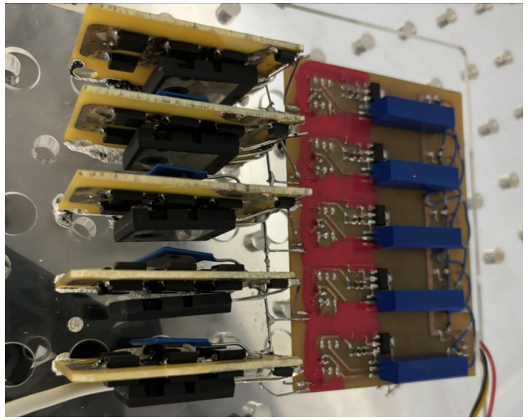
→ See Claudia and Carolina presentations

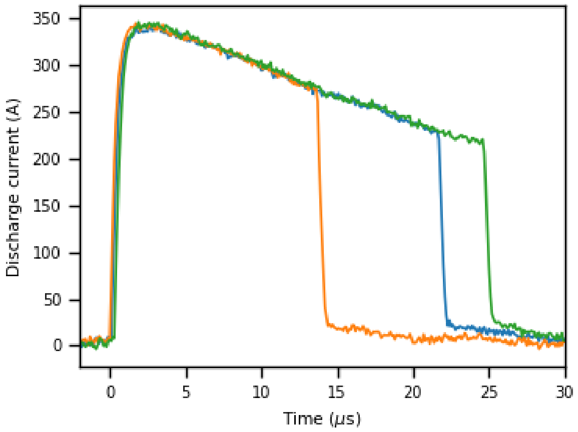
Discharge Plasma Source at ICL

Imperial College London



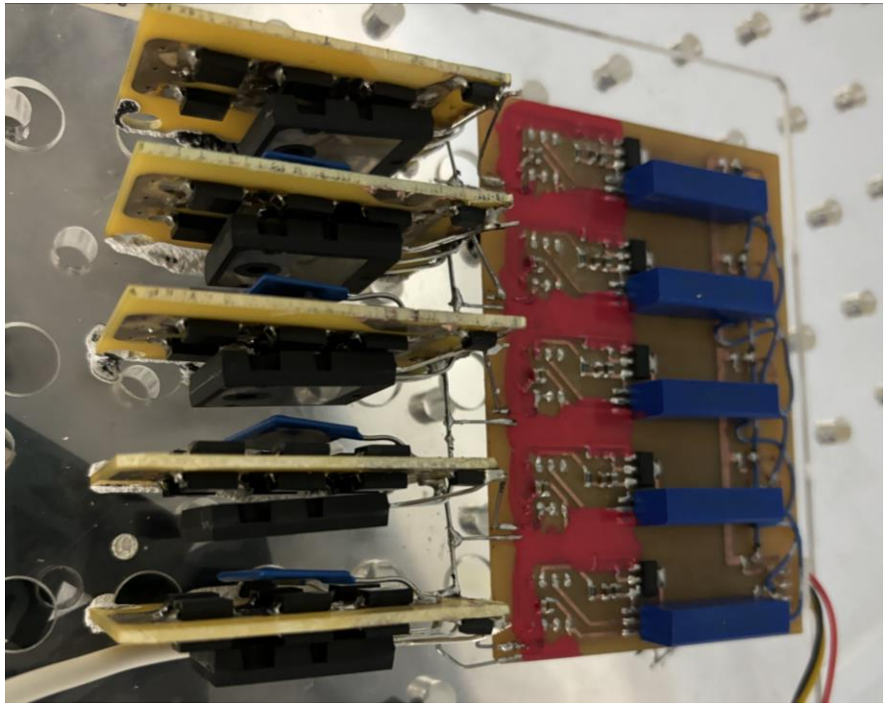
Parameter	ICL Value	CERN Value	Unit
Tube length	1	10	m
Diameter	19.5	26	mm
Discharge gap	15	25	cm
Gas pressure	0.01 – 1.5	0.01 – 1	mbar
Discharge current	~ 400	100 – 600	A
Discharge time	5-25	~25	μs
Plasma electron density	1 – 10	0.1 – 20	10^{20} m^{-3}
Ionisation degree	1	~ 20	%

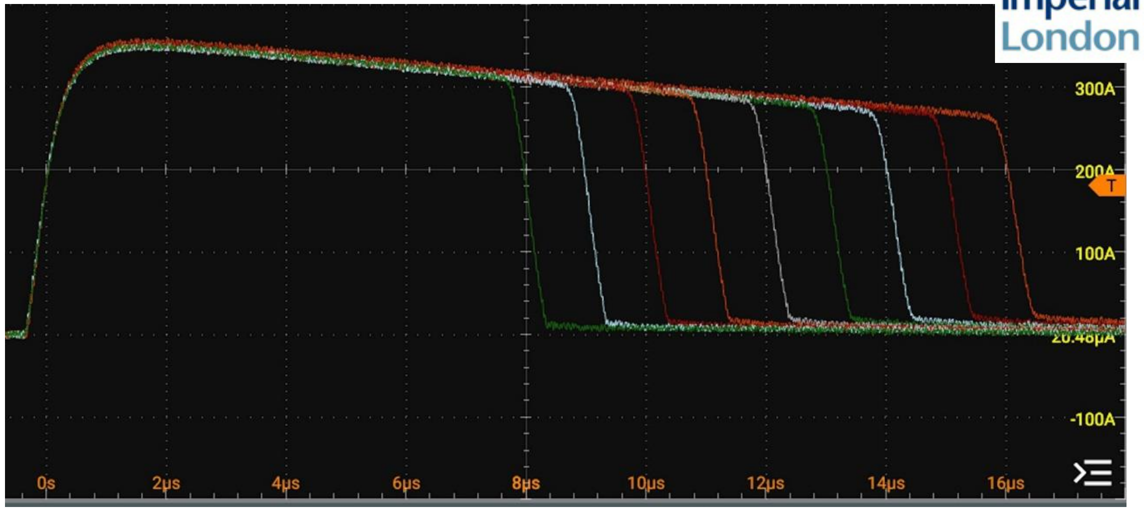




High voltage switch

Imperial College London



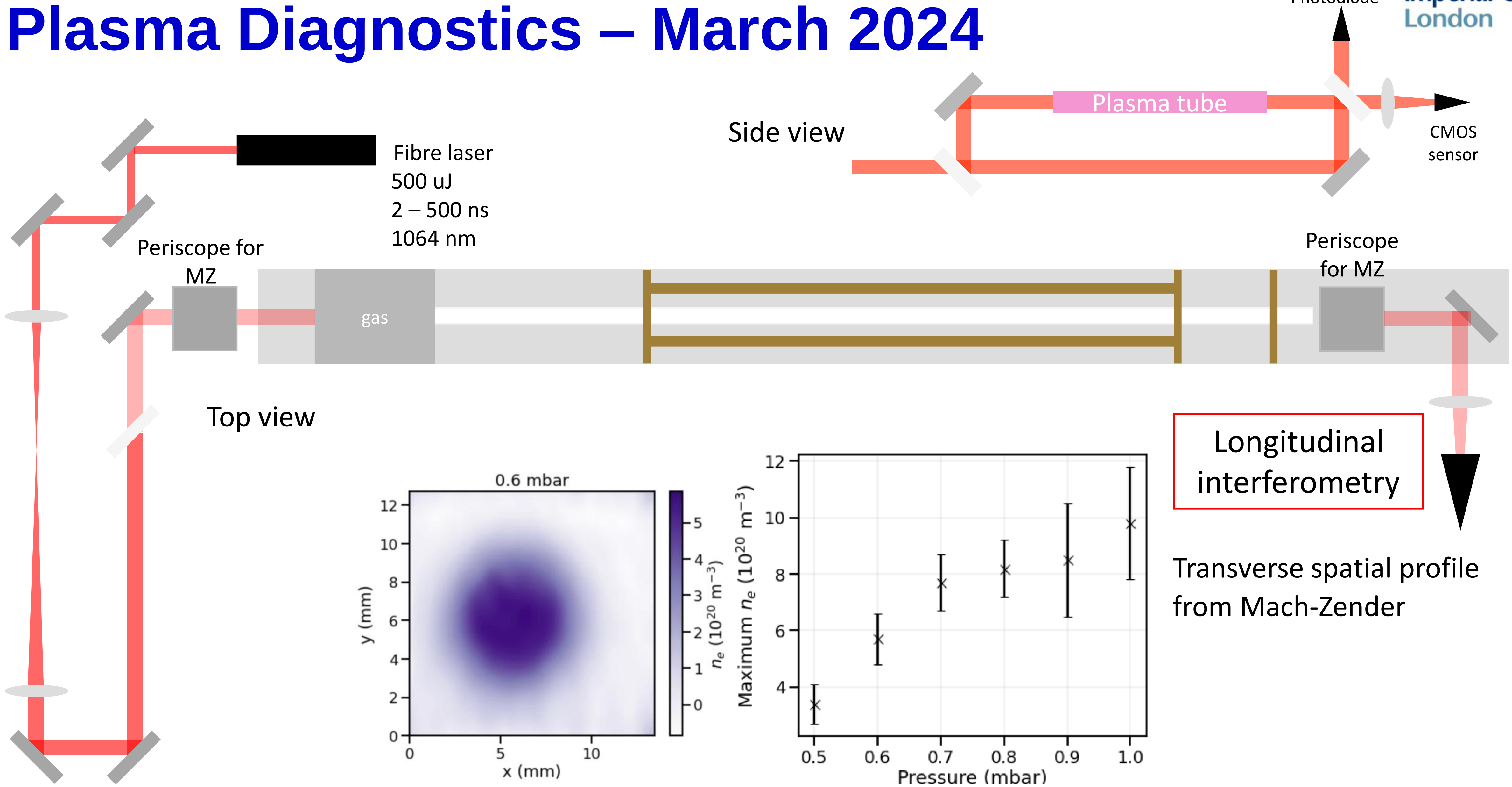


High repetition rate operation tested on resistive-inductive dummy load

- Successful at 630 A peak 500 kHz
- And 500 A peak operation at 1 MHz

Compact, 16 cubic inch
Tolerates full current ringing
Multi-stage optically isolated trigger
Arbitrary pulse width

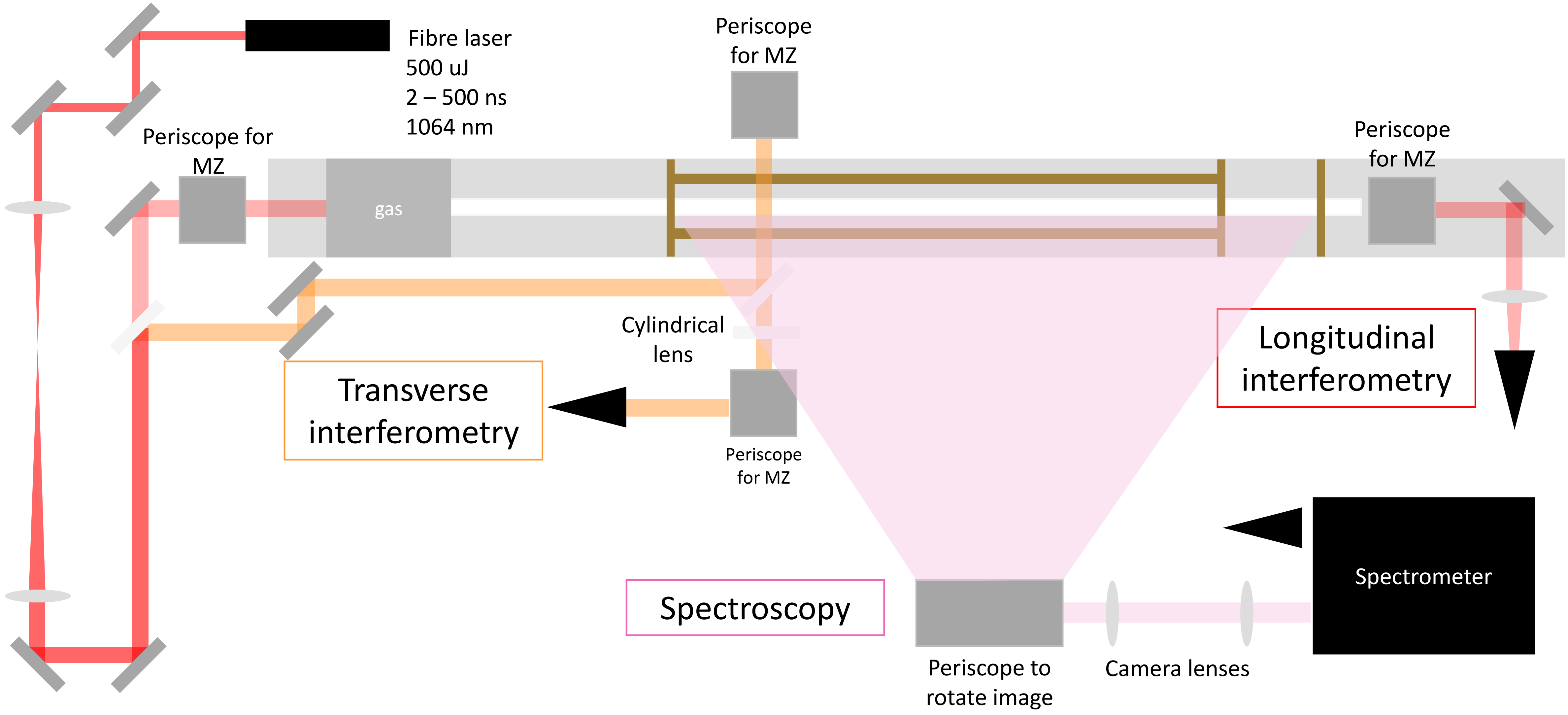
Plasma Diagnostics – March 2024



Transverse spatial profile from Mach-Zender

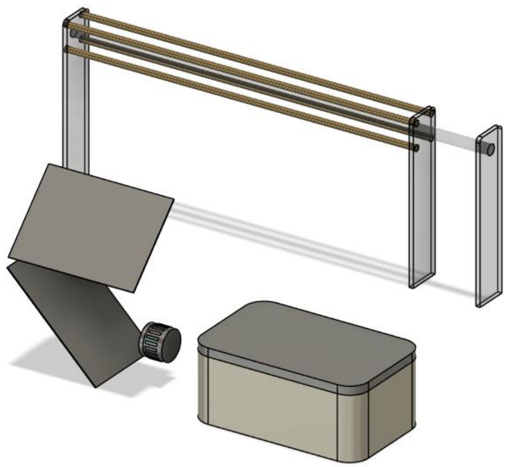
Plasma Diagnostics – November 2024

Imperial College London



Emission Spectroscopy

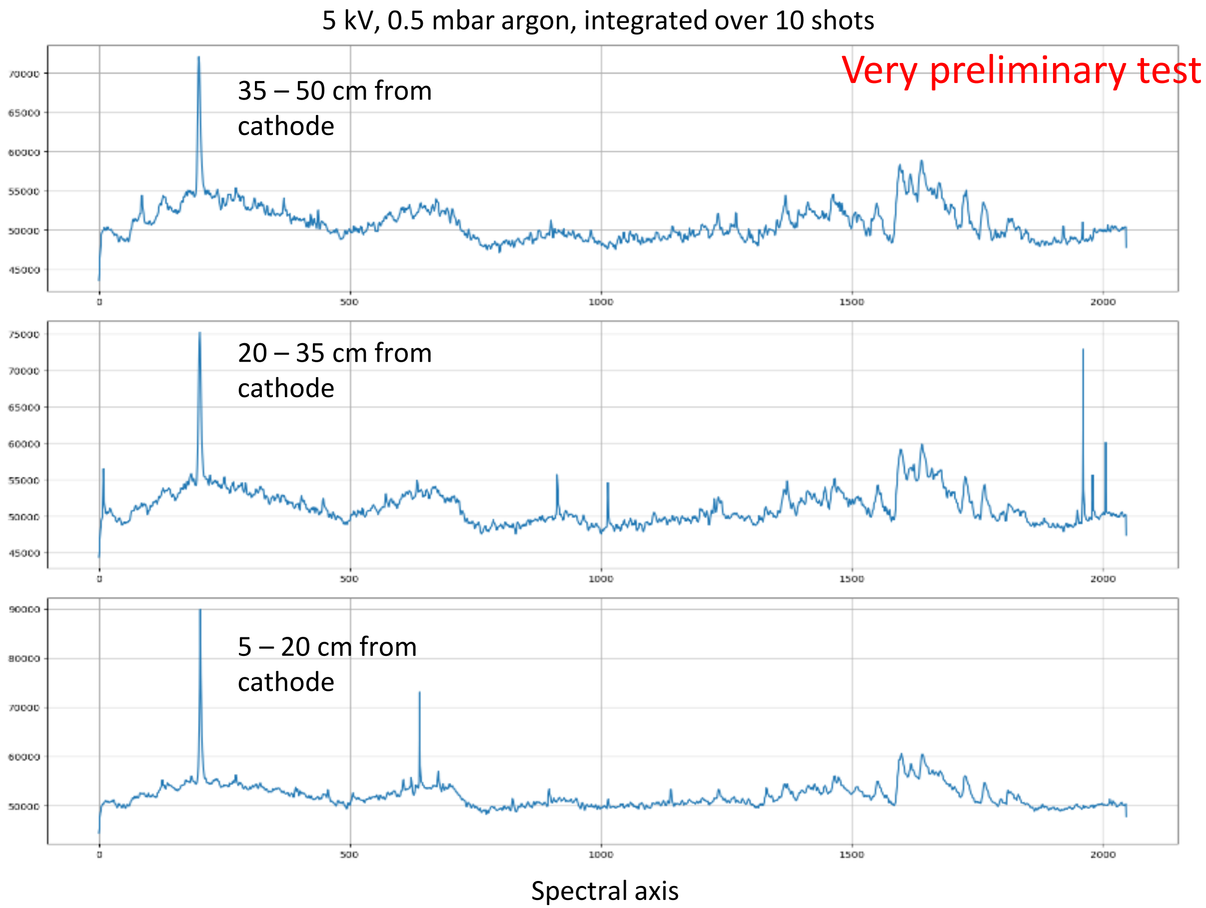
Bentham M300 Czerny-Turner spectrometer used to measure spectrum over 1 m tube



Aberrations corrected with cylindrical lens and post-processing

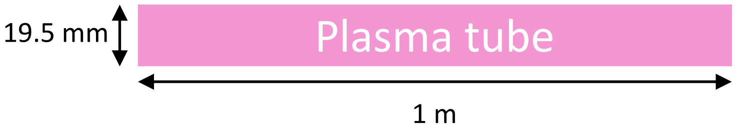
Imaging spectrometer currently being tested

Spectra integrated over different parts of tube

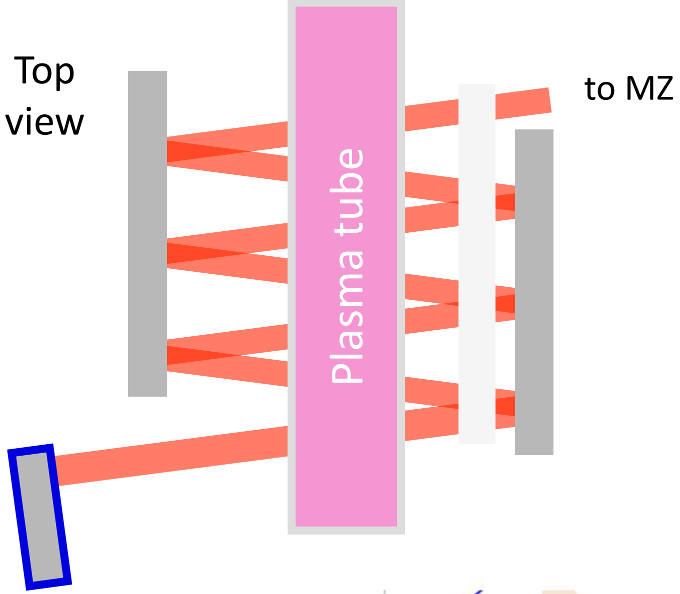


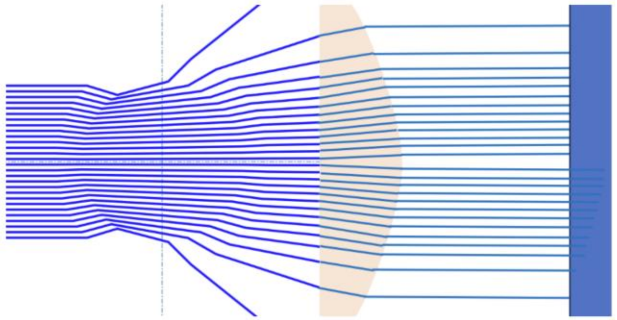
Suggests uniformity measurements averaged over ~15 cm are possible

Transverse Multi-Pass Interferometry



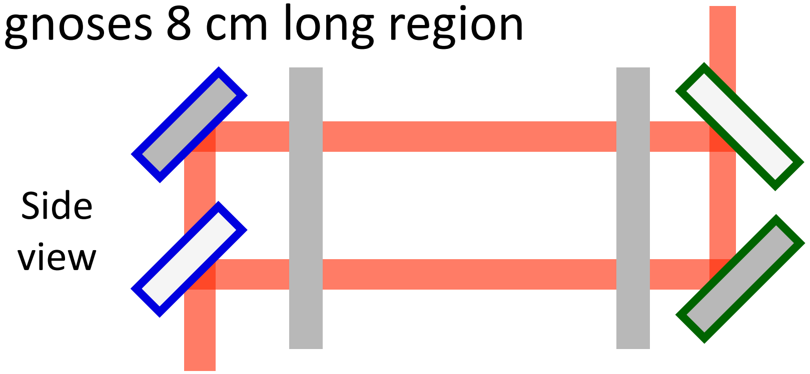
Need many (~20) passes for measurable phase shift

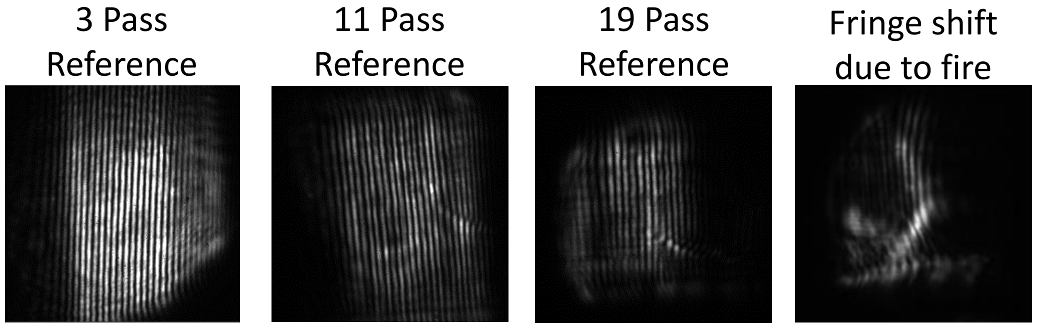




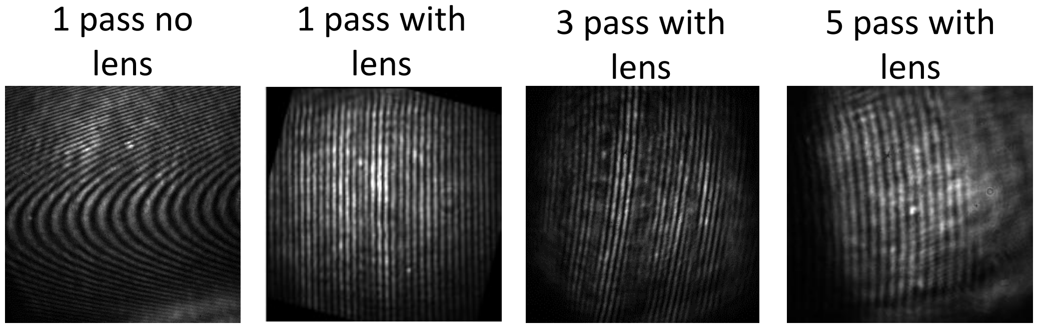
Demonstrated 19 pass MZ configuration in air

- Diagnoses 8 cm long region



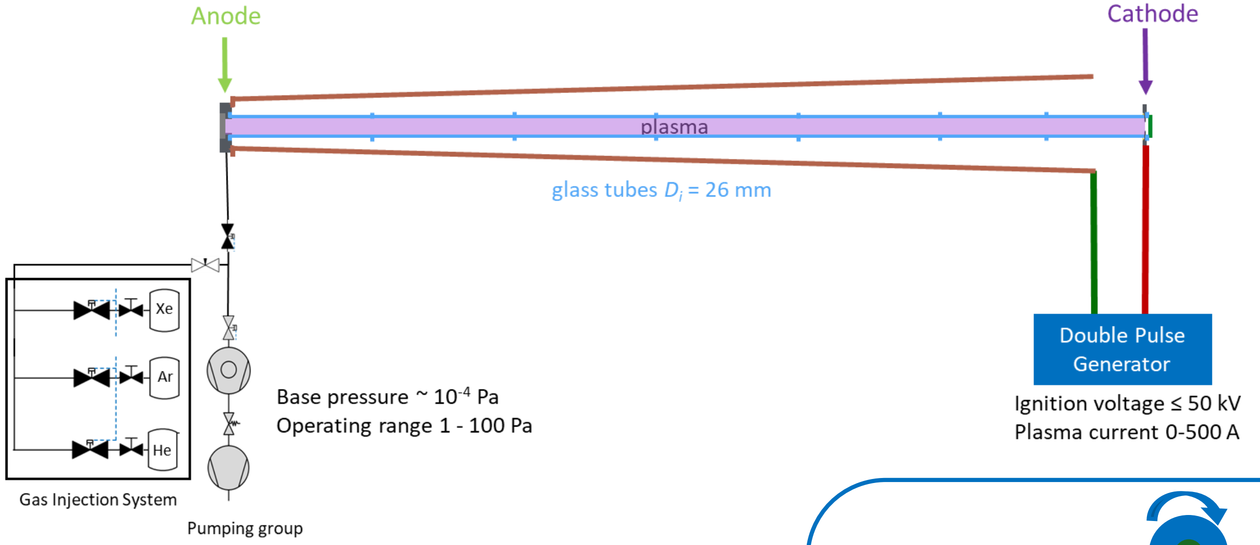


Implementation through tube in progress

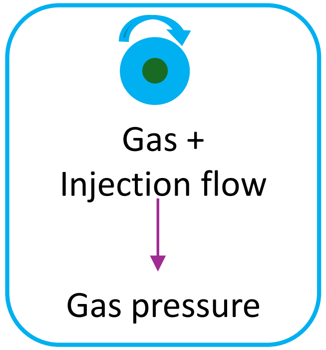


DPS plasma density reproducibility

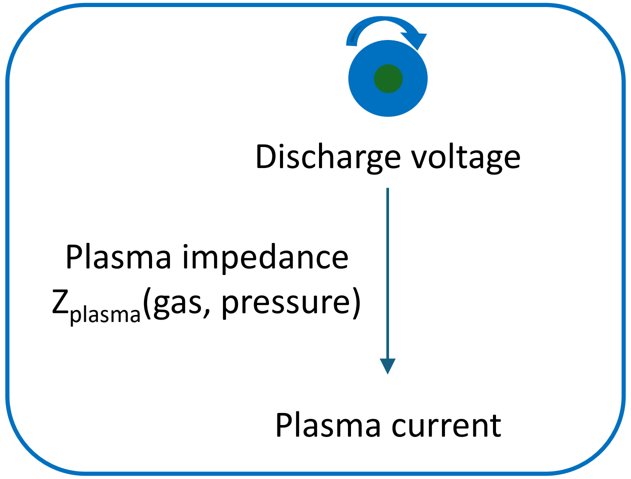
- Improve the control of the pressure and current of the discharge
- Room temperature controlled (variations <0.1° C)
- Series of 200 discharges, at 0.1 Hz repetition rate



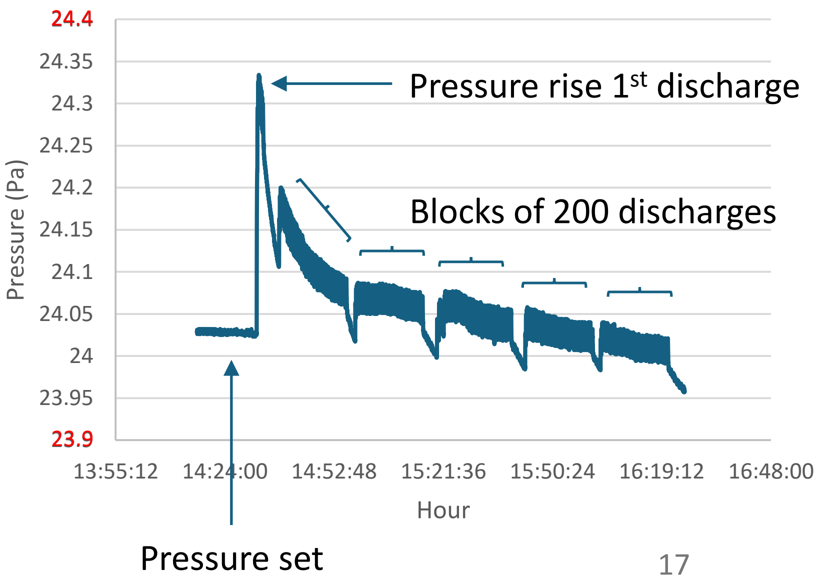
Parameters:
Gas: Ar
Pressure: 24 Pa
Voltage: -6.32 kV → 500 A
Pulse duration: 25 µs
Plasma length: 10 m



(measured capacitive gauge, **gas independent**)



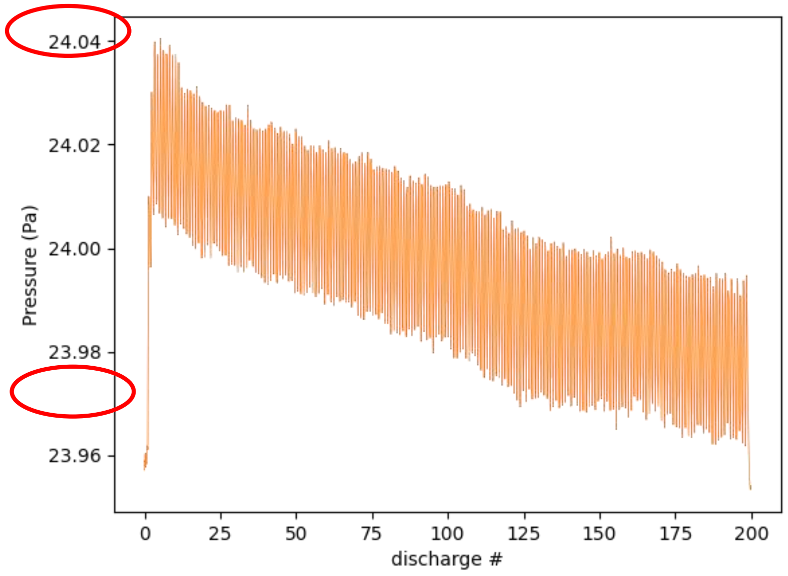
04/07/2024



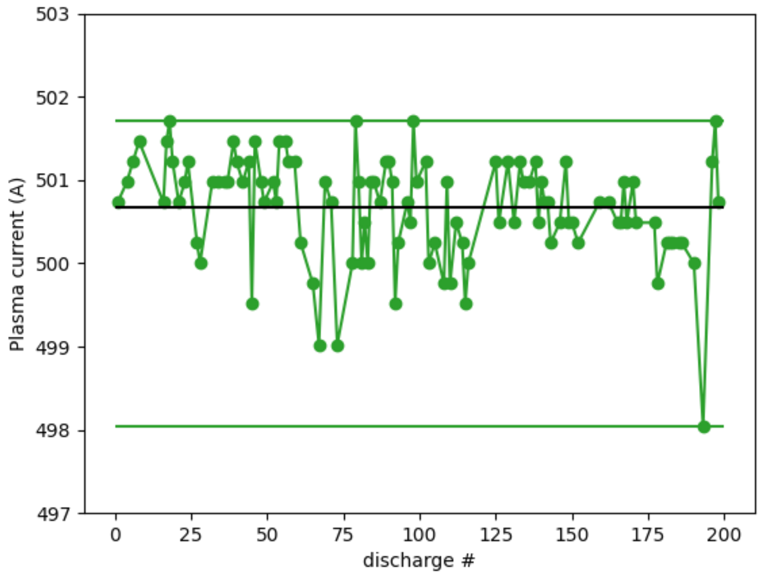
DPS plasma density reproducibility

Over 200 discharges:

< 0.2% variation gas pressure



< 0.5% variation peak current

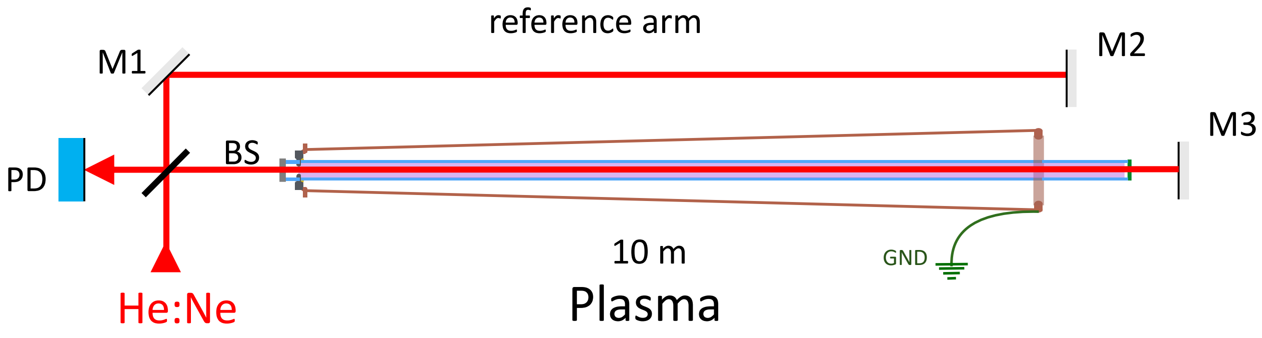


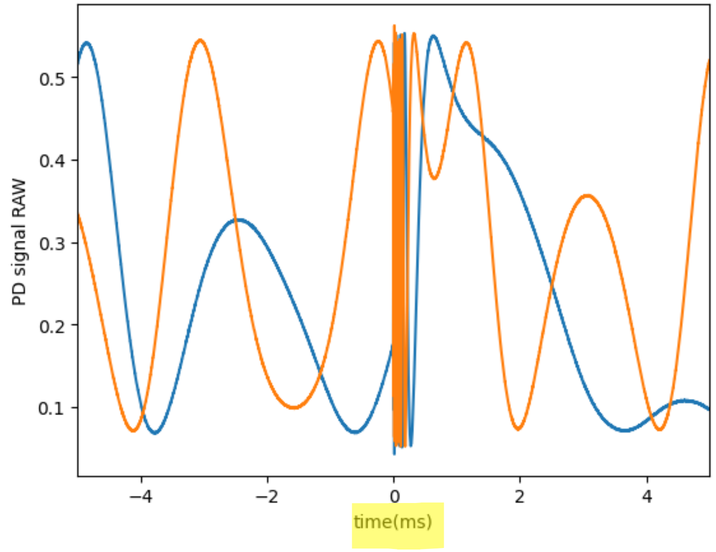
Parameters:
Gas: Ar
Pressure: 24 Pa
Voltage: -6.32 kV → 500 A
Pulse duration: 25 µs
Plasma length: 10 m

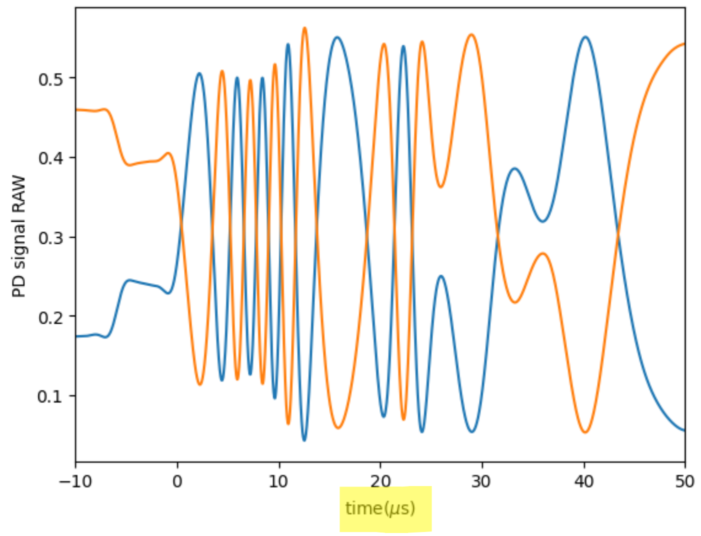
Plasma density ?

longitudinally integrated interferometry

Longitudinally integrated interferometry







- ► Michelson interferometer
- ► Measurement arm (plasma) adds a phase shift ϕ_i proportional to the plasma density n_e:

$$\phi_i = \frac{n_e}{r_e \, \lambda_i L}$$

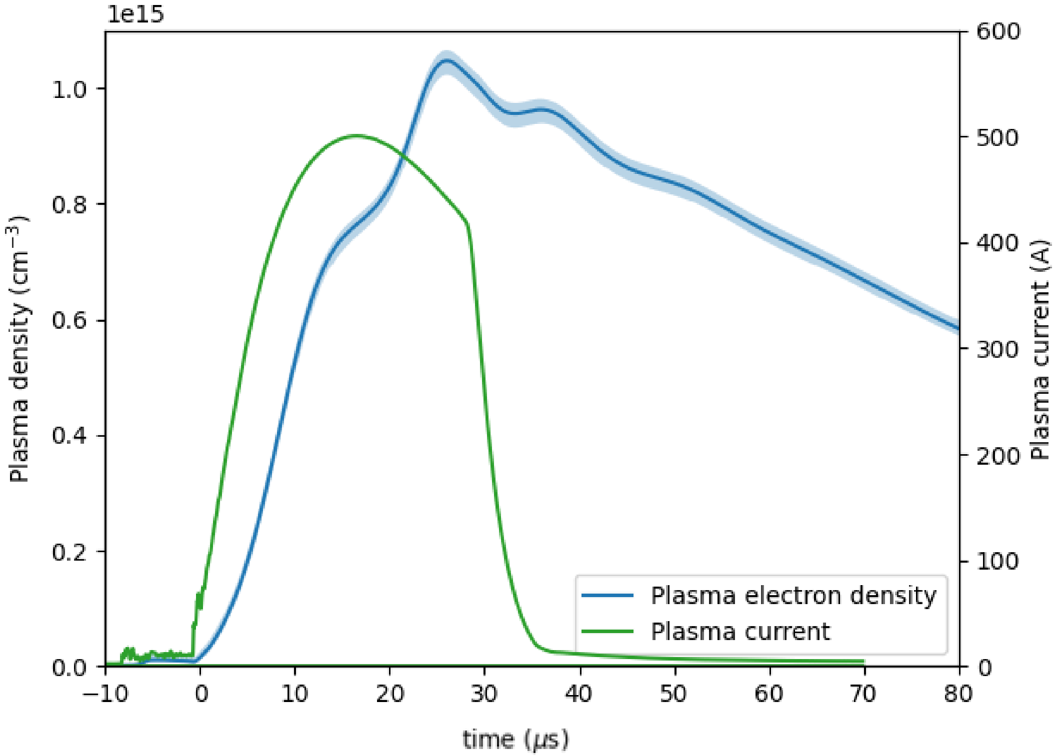
where r_e is the classic electron radius ($r_e = 2.82 \times 10^{-15}\ m$), λ_i is the laser wavelength and L is 2x the length of the plasma.

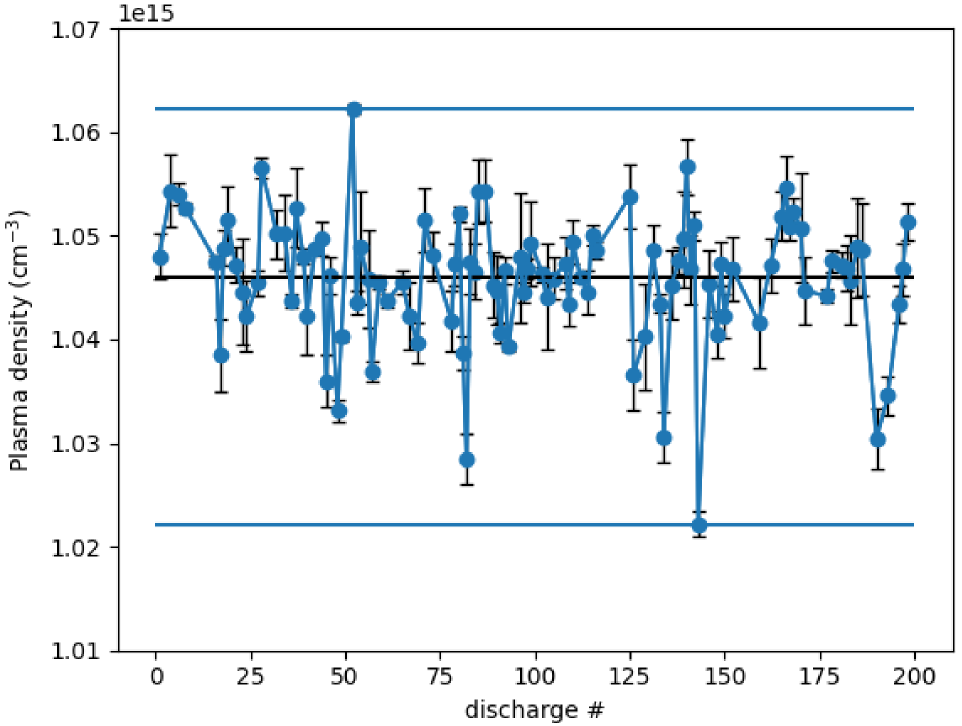
Every interferogram has a different “history”, but they tell the same “story”

DPS plasma density reproducibility

► Shot-to-shot plasma density variation was evaluated over **200 consecutive discharges** with longitudinal-integrated interferometry

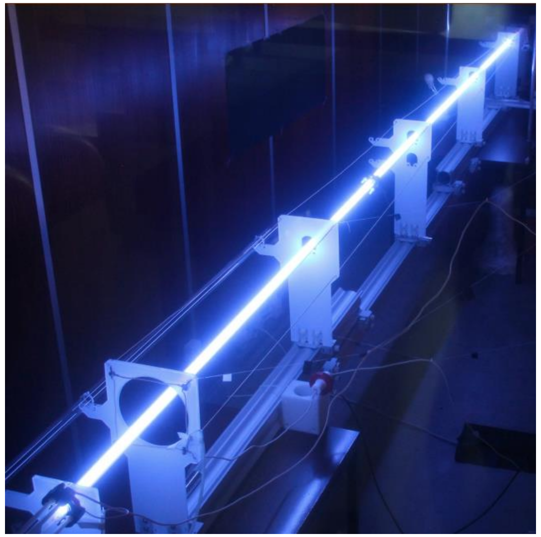
Parameters:
Gas: Ar
Pressure: 24 Pa
Voltage: -6.32 kV, 500 A
Pulse duration: 25 µs
Plasma length: 10 m





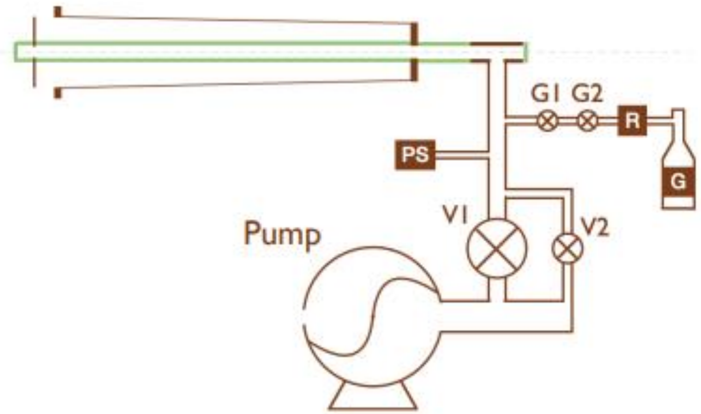
<2% plasma peak density variability

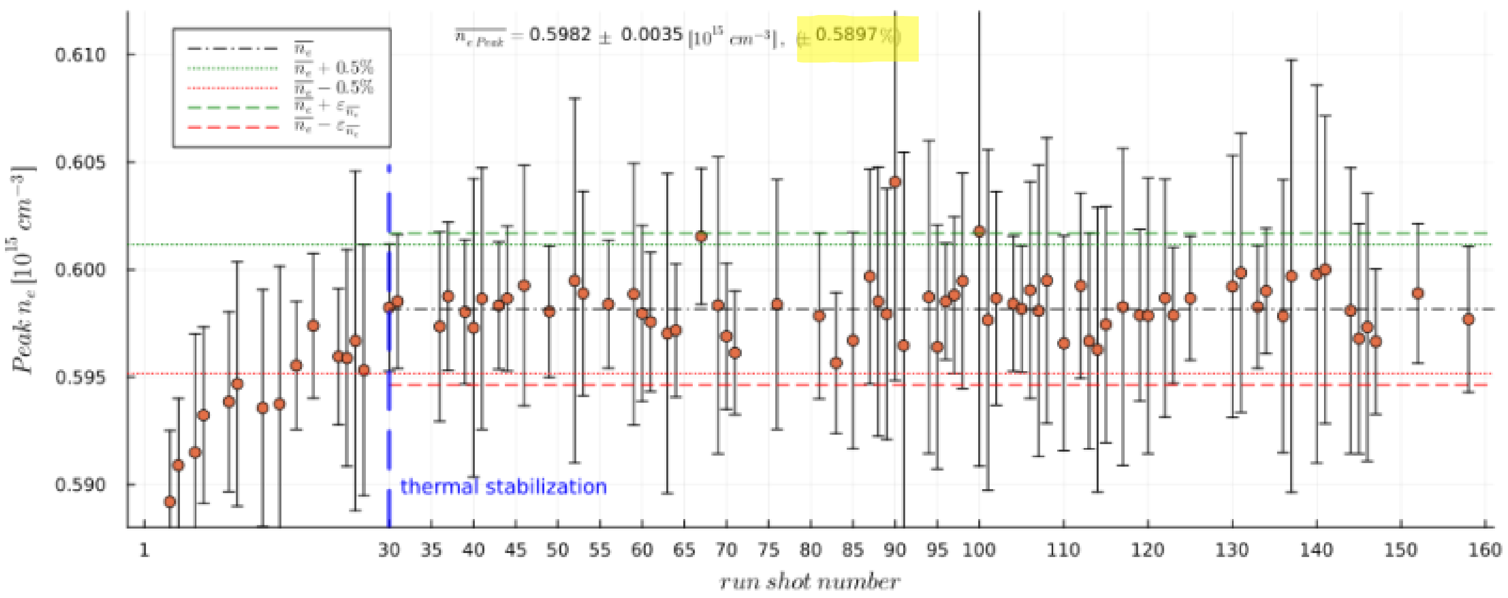
IST AWAKE DPS stability runs (in progress)



tube ϕ_i = 25 mm , L = 5 m

I_{heat} = 400 A, P = 18 Pa





Automatic operation

Gas renewal after each discharge

Fixed repetition rate (2 min)

$n_a = 4.40 \times 10^{15}$ cm^{-3}

$n_e = 0.60 \times 10^{15}$ cm^{-3}

J = 81.5 A cm^{-2}

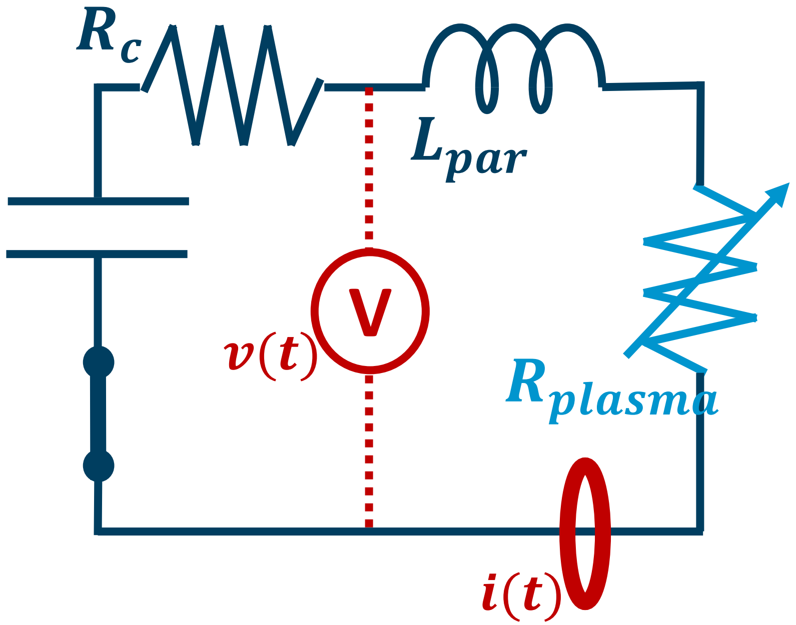
n_e/n_a = 13.6 %

DPS plasma electrical characterisation

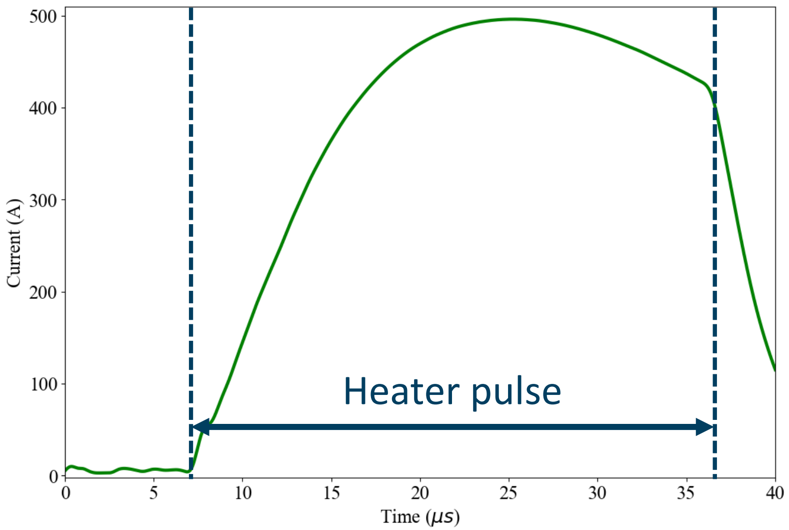
Plasma resistance measurements

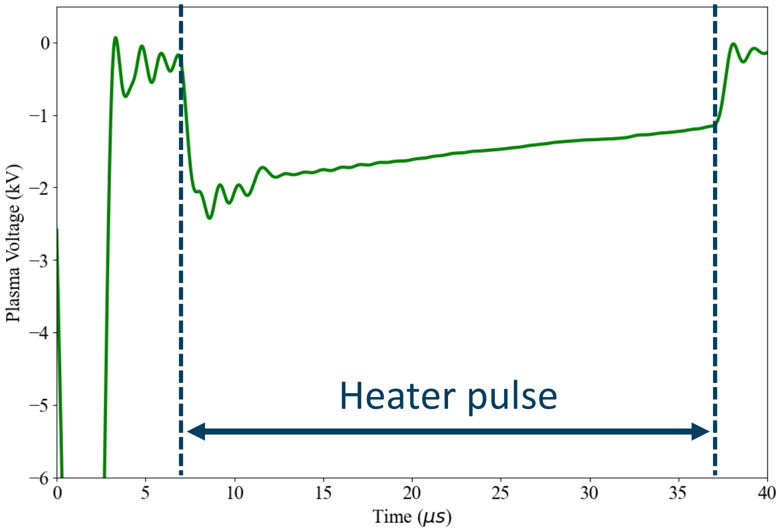
In the CERN 10 m set-up, we can measure the applied voltage and the plasma current

During the heater pulse, the pulse generator output can be simplified to an RLC circuit → calculate the plasma resistance



$$r_{plasma}(t) = \frac{v(t) - L\frac{di}{dt}}{i(t)}$$





DPS plasma electrical characterisation

Plasma resistance measurements

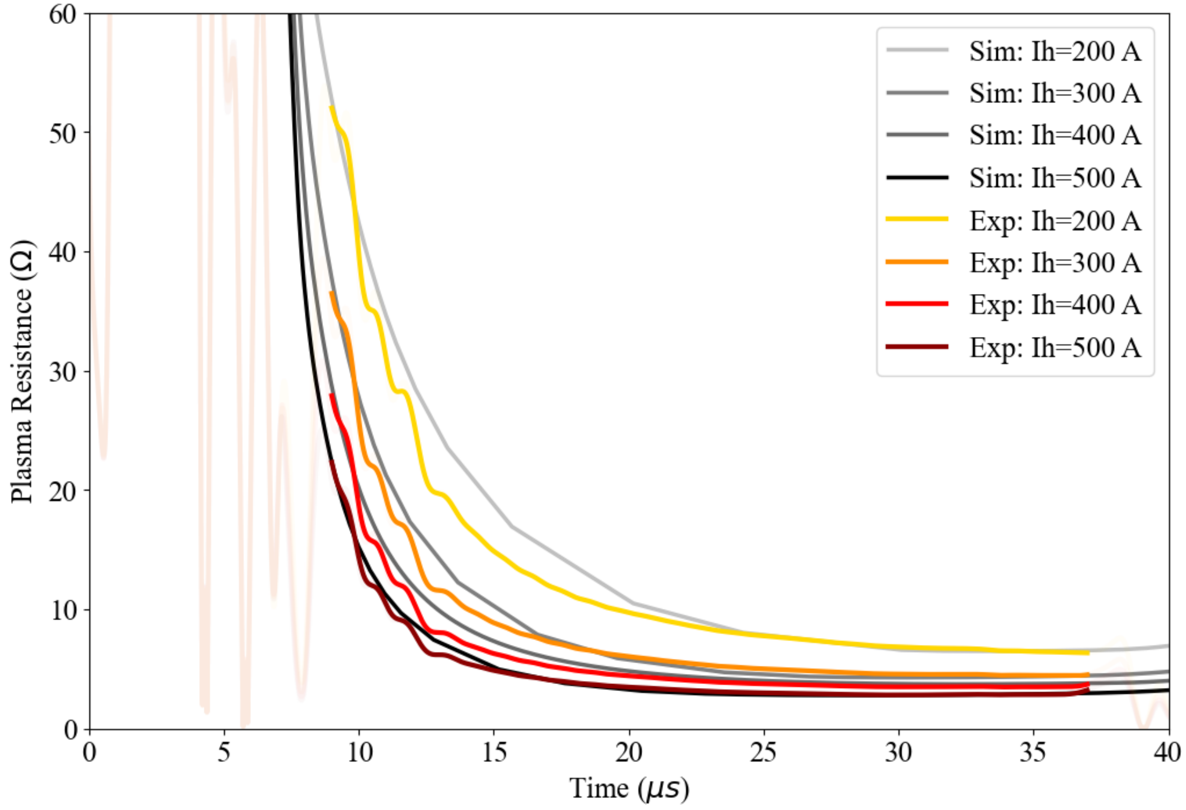
Pspice simulation → modeling the electric circuit of the pulsed power generators
→ Very important for the design

Compare experimental results with electrical simulations

Plama resistance model obtained from Cassie's Arc Model:

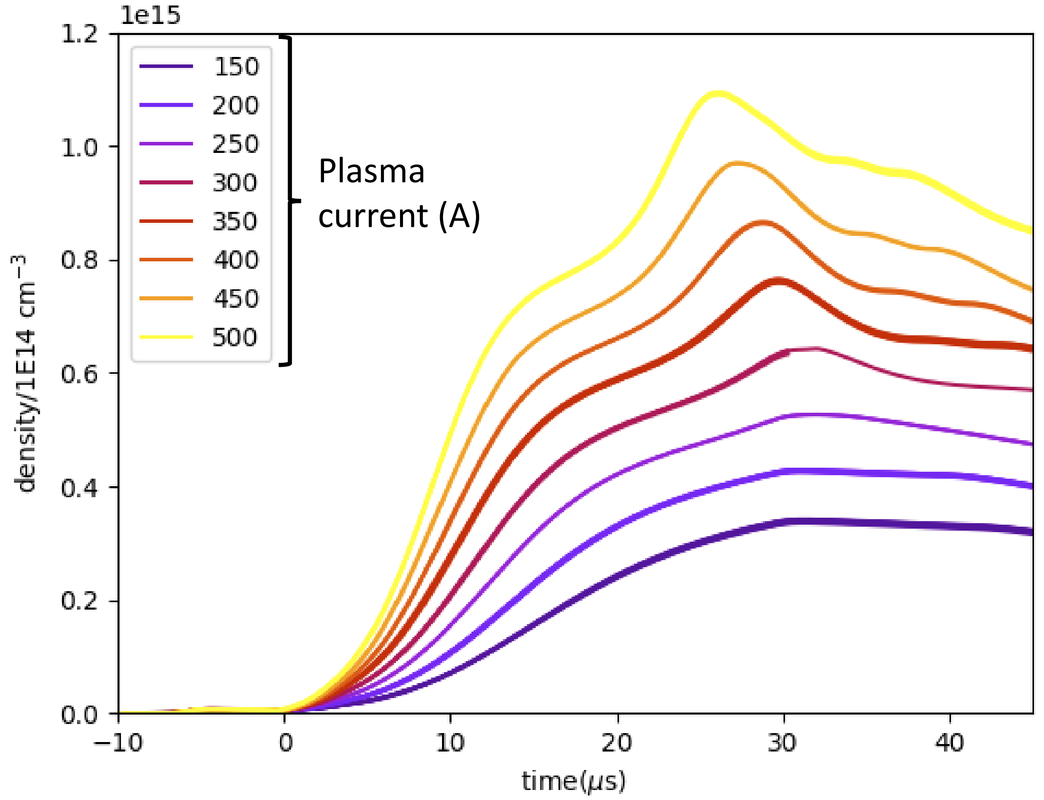
$$r(t) = \int \left(1 - \left(\frac{v(t)}{V_0}\right)^2\right) \frac{r(t)}{\theta} dt$$

r: time-varying arc resistance
v: instantaneous arc voltage

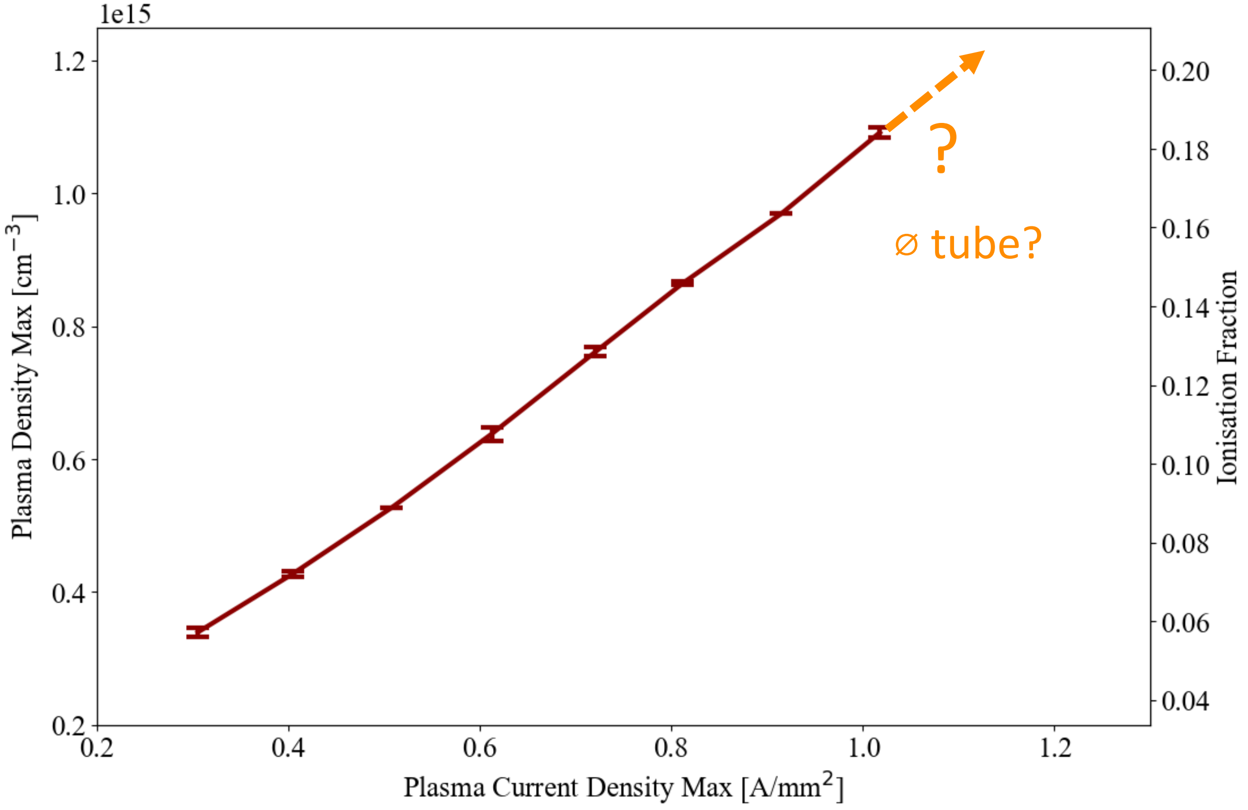


Plasma current density scan

Parameters:
Gas: Ar
Pressure: 24 Pa
Pulse duration: 25 µs
Plasma length: 10 m
⌀ **tube:** 25 mm tube

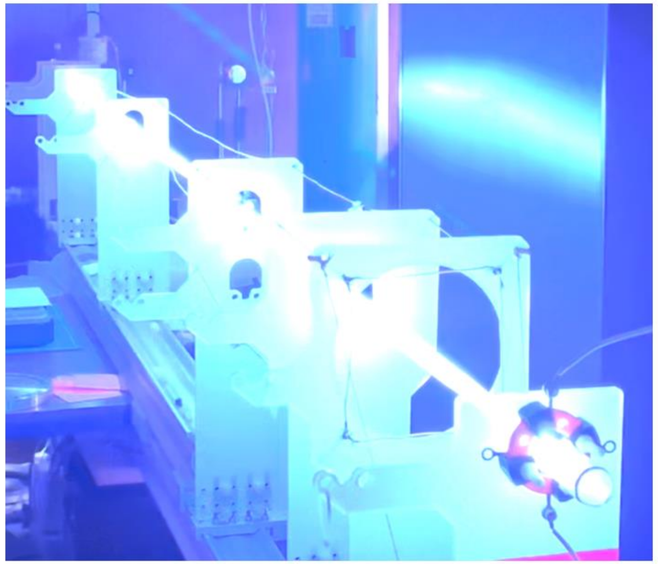


- Plasma ionisation fraction scales linearly with the power delivered
- Semiconductor devices' current rating is limiting the maximum power delivered



IST AWAKE DPS stability runs (in progress)

TÉCNICO LISBOA



tube ϕ_i = 12 mm , L = 3.3 m

I_{heat} = 400 A, P = 10 Pa

$n_a = 2.47 \times 10^{15}$ cm^{-3}

$n_e = 0.94 \times 10^{15}$ cm^{-3}

J = 353 A cm^{-2}

n_e/n_a = 37.9 %

tube ϕ_i = 25 mm , L = 5 m

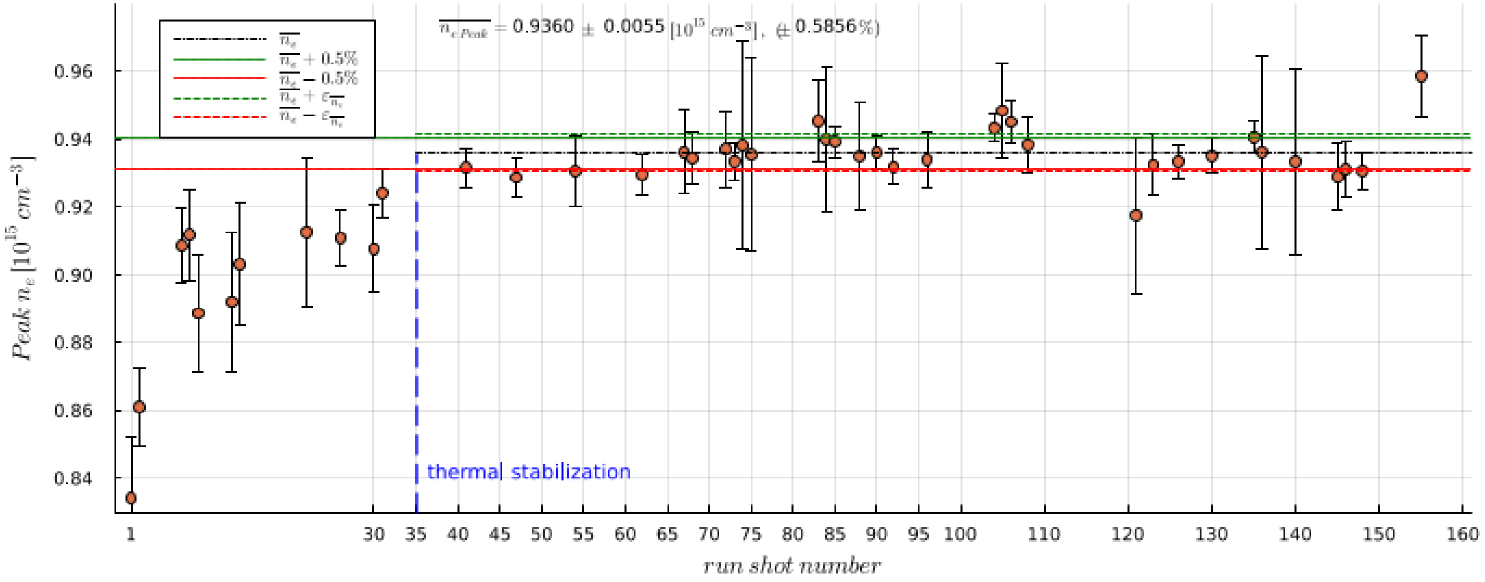
I_{heat} = 400 A, P = 10 Pa

$n_a = 4.40 \times 10^{15}$ cm^{-3}

$n_e = 0.60 \times 10^{15}$ cm^{-3}

J = 81.5 A cm^{-2}

n_e/n_a = 13.6 %



Comparison tube 25 mm / 12 mm

@ 400 A & 10 Pa

J increases 4.3 X

n_e/n_a increases 2.8 X

Work in progress

Systematic data for

25mm and 12mm diameter tubes

IST AWAKE DPS plans for 2025

Tests with high current densities 0.4 - 1.0 kA/cm2 in tubes 12-25 mm

Length scalability demonstration - up to 5 plasmas

High precision gas pressure control

Improvement of interferometry precision

Precise tube temperature control

Operation at high reproducibility

New electric kit

Last results from CERN

1. New 3 m set-up in preparation of Thomson scattering measurement
2. Radial scan with longitudinal average interferometry

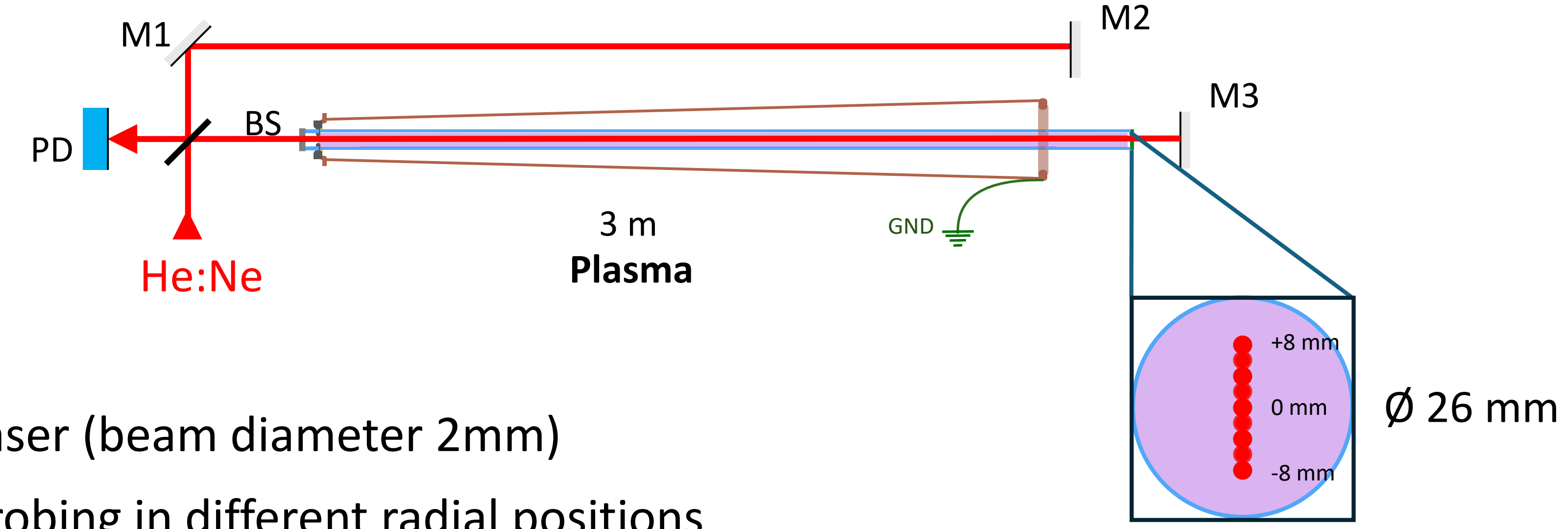
Thomson scattering on DPS: Fall/winter 2024

→ **local** plasma density measurement along the source (at a specific point in time)

→ time-scan also possible: different laser-discharge delays → benchmark time-evolution density

Last results: radial profile

Longitudinally integrated interferometry



Parameters:
Gas: Ar
Pressure: (23.94±0.02) Pa
Peak current: (400±3) A
Heater voltage: 6.27 kV
Pulse duration: 25 µs
Plasma length: 3 m

Laser (beam diameter 2mm)

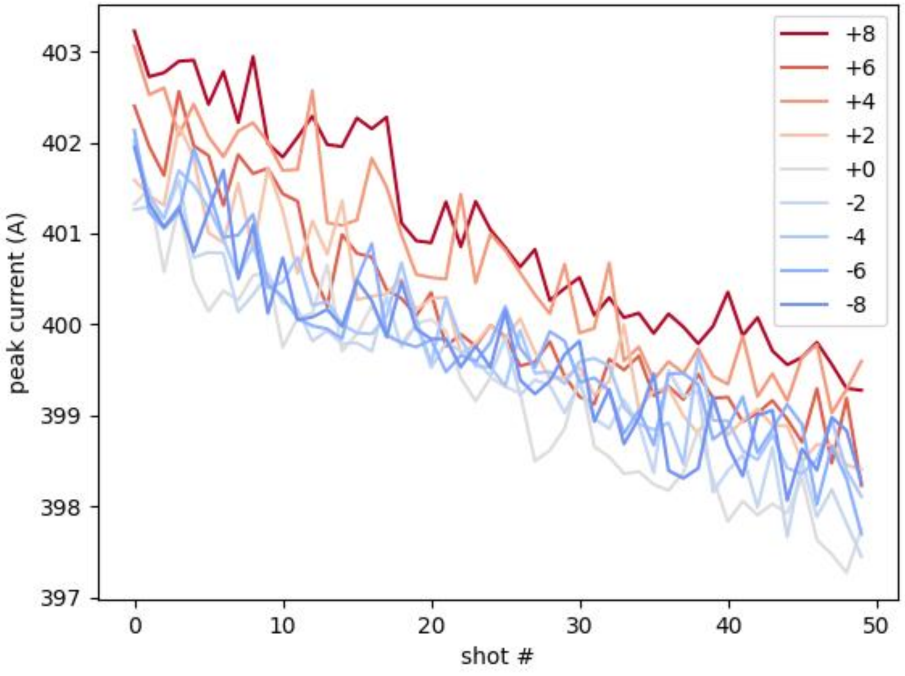
probing in different radial positions

Last results: radial profile

Stability of the peak current and pressure among sets

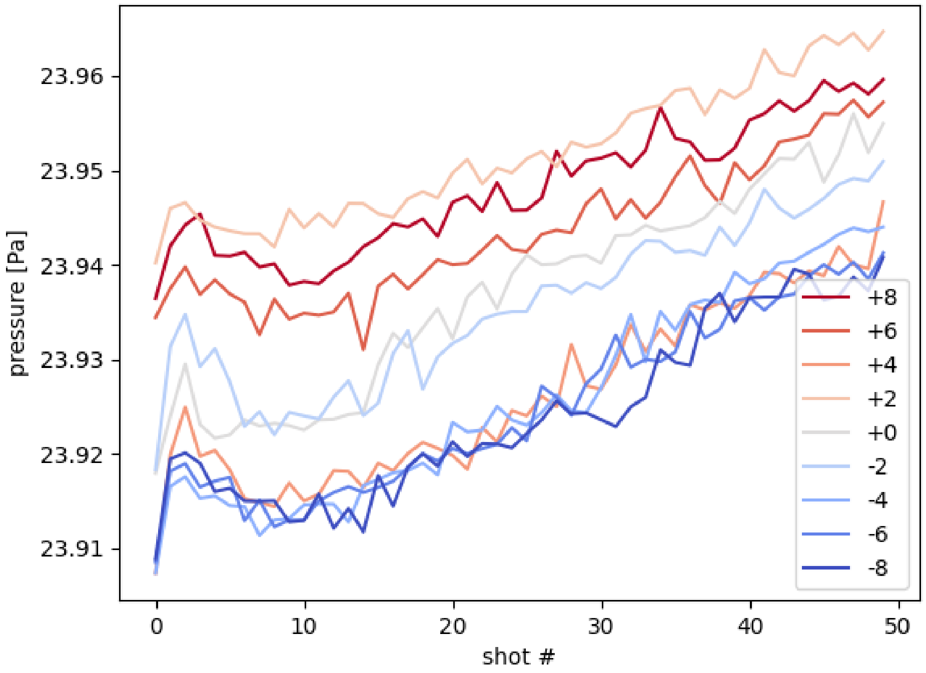
First generation (2021) of pulsed power supplies

Peak current



- Rep rate 0.5 Hz → over the 50 repetitions **decreases**
- Still very reproducible among the different sets
- **Overall → current (400±3) A** < 1 %

Pressure



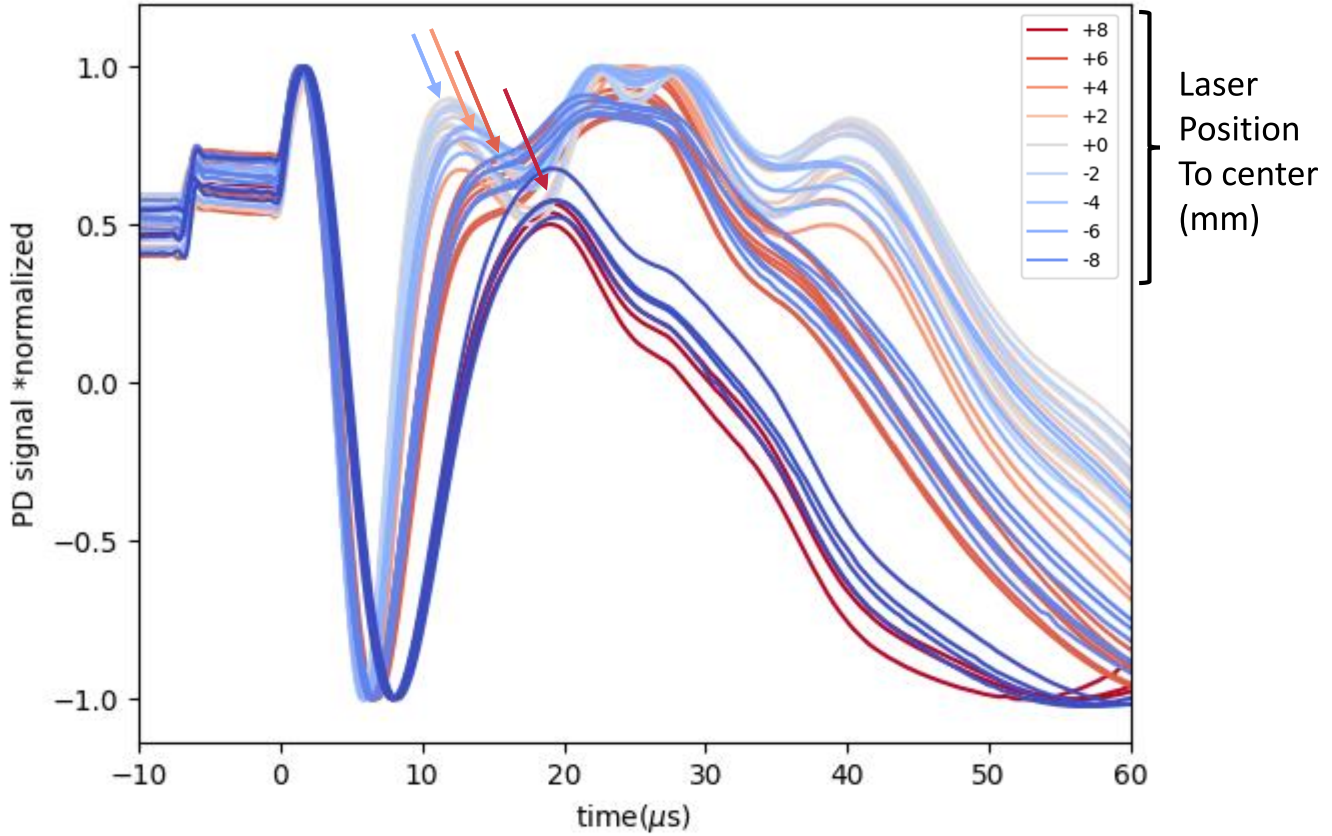
- over the 50 repetitions →pressure rising ~ 0.02-0.03 Pa
- **Overall → pressure (23.94±0.02) Pa (~ 0.1 %)**

Last results: radial profile

Raw data

*normalized to -1 to 1 (domain of arcsin)

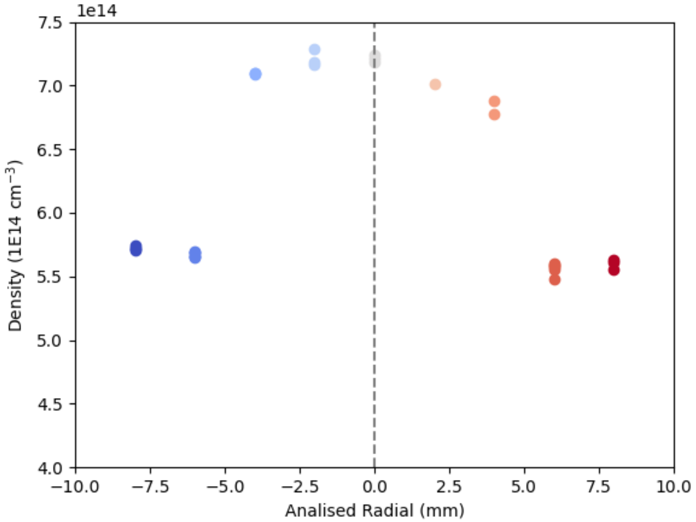
- Selected shots (same phase)
- Clear difference between radial positions
  - 4 groups
    - |8| mm
    - |6| mm
    - |4| mm
    - < |2| mm
  - Number of fringes → density
  - and position of 1st stagnation point → time evolution of density

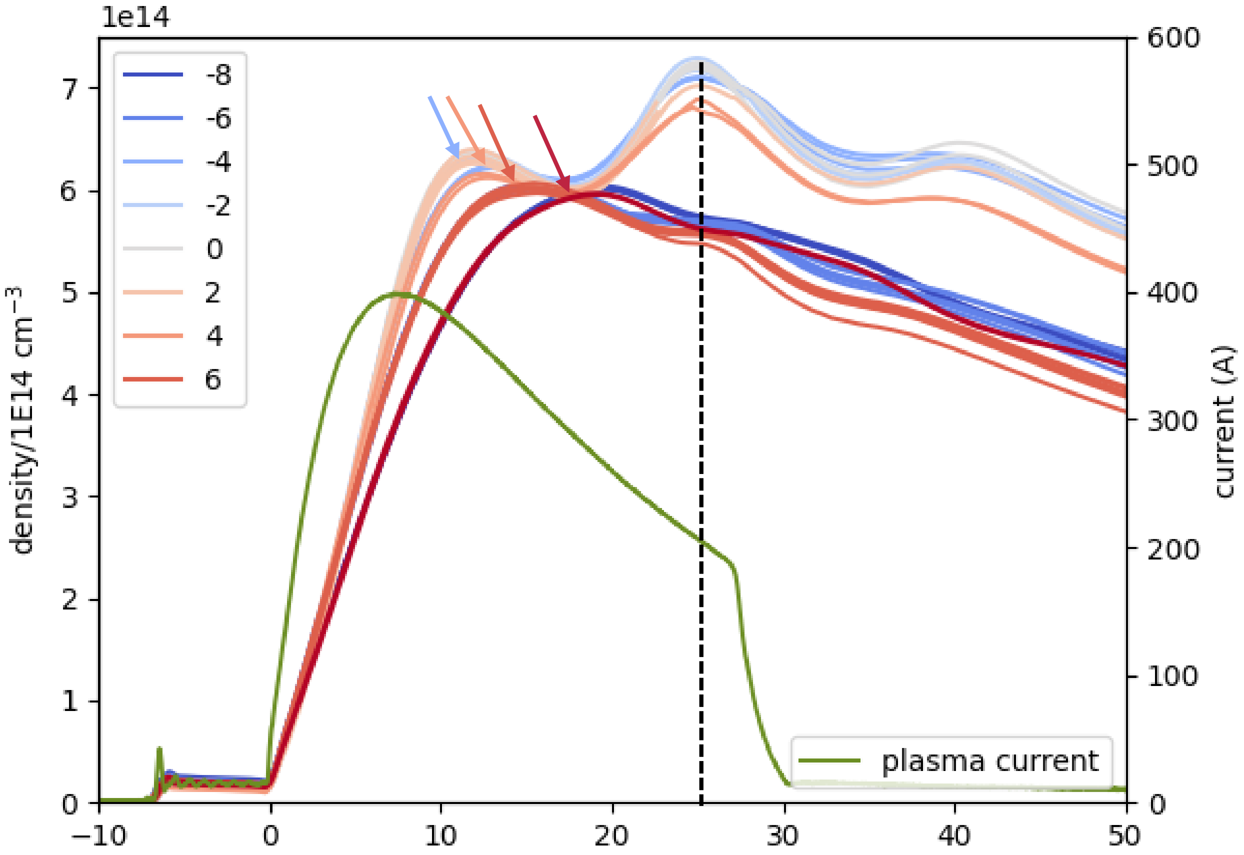


Last results: radial density profile

- 4 groups
  - |8| mm
  - |6| mm
  - |4| mm
  - < |2| mm

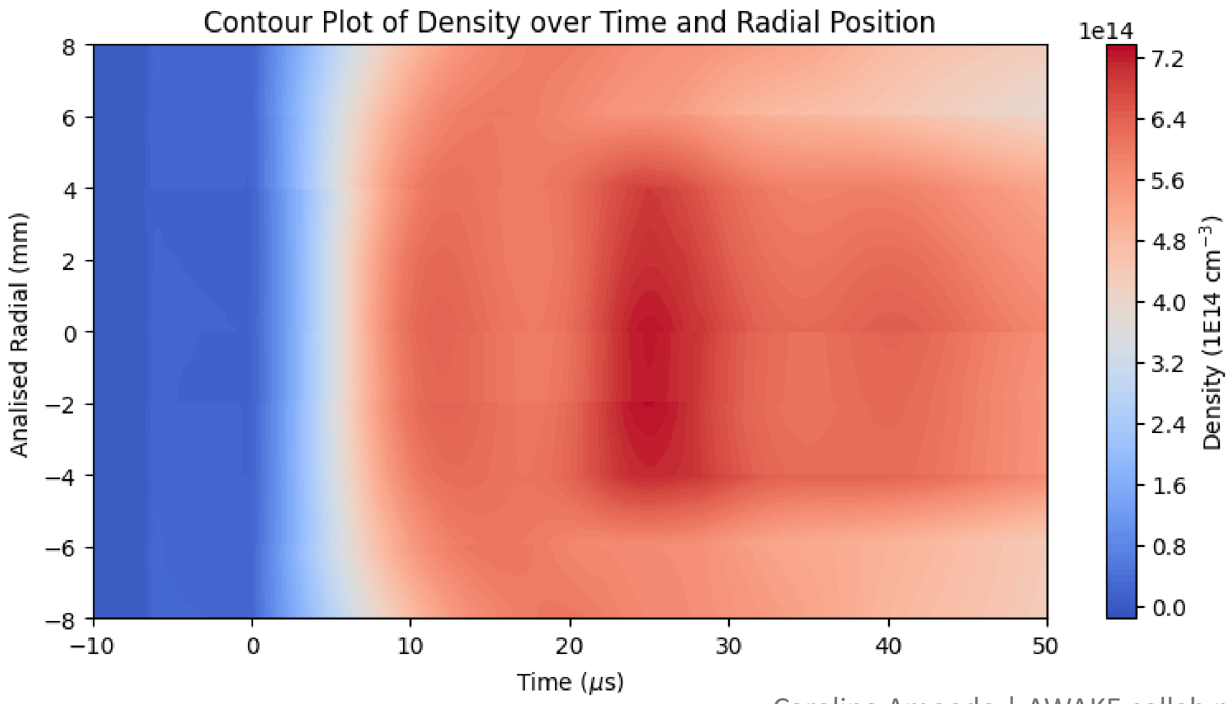
At peak density (r=0)
t=25 µs, radial profile:

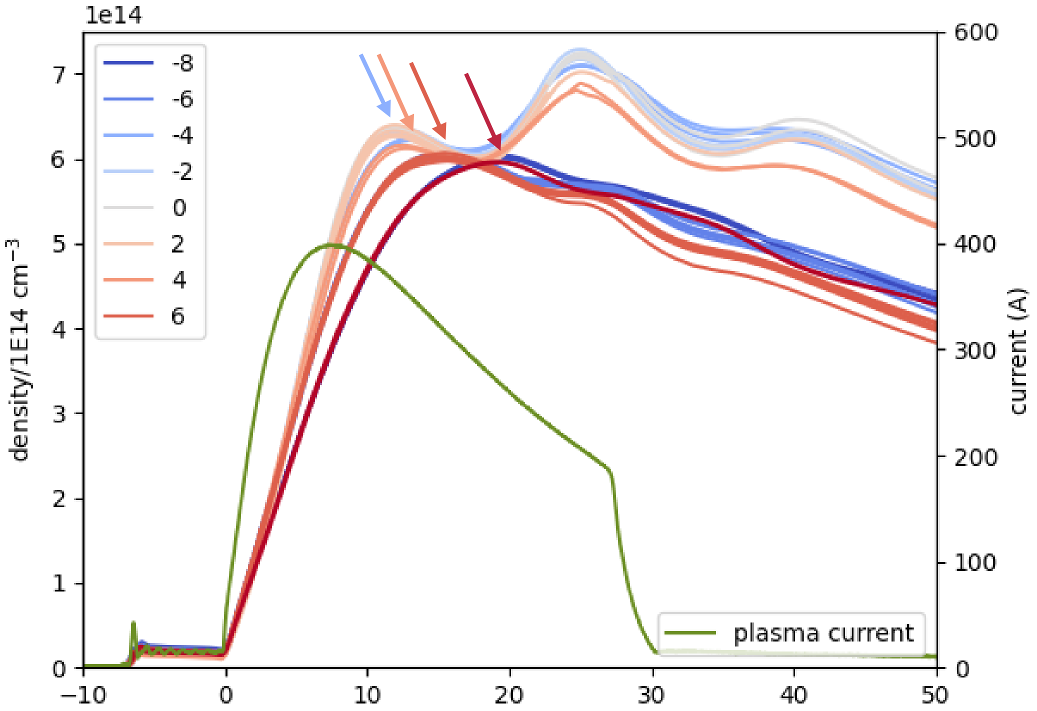




Last results: radial density profile

- 4 groups
  - |8| mm
  - |6| mm
  - |4| mm
  - < |2| mm





Summary

- Hardware consolidation/developments to support stability, although some reproducibility issues on HPS as seen by TS
- Diagnostic developments at institutes and CERN → comparison and combination to further characterize plasma
- Reasonable match (~ 30% difference) between CO_2 interferometry and Thomson scattering on HPS in steady state
- Axial density profile on HPS: +/- 6% uniformity over 0.5 m for helical antennas, ring antenna results coming soon!
- DPS longitudinally integrated density measured by interferometry < 2% shot to shot reproducibility (at CERN + IST)
- First radial scan of 3 m long DPS showing flat density over ~ 4 mm diameter
- Axial density profile on 3 m DPS due by the end of the year

2024 PhDs/publications:

- 2 PhDs thesis completed at University of Madison (Marcel and Michael)
- M. Zepp, *"Direct measurement of the 2D axisymmetric ionization source rate in a helicon plasma for wakefield particle accelerator applications"*, Physics of Plasmas, DOI
- C. Stollberg, *"First Thomson scattering results from AWAKE's helicon plasma source"*, Plasma Physics and Controlled Fusion, DOI

Thank you for your attention