Introduction to Plasma Diagnostics section

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Workshop EuPRAXIA PP – WP10 – Plasma Components
Desy 27-28 January 2025

Layout

-) Density requirements in EuPRAXIA plasma components:
average density, plasma length – (stability-accuracy, transverse dimension).

-) Diagnostics/metrology needs for test/optimization and operations.

-) State-of-the-art:
Interferometry – Two-arm interferometer (TAI), wavefront sensors, and Second-harmonic dispersion interferometer (SHDI).
Other diagnostics - Spectroscopy (pressure broadening), shadow/schlieren, Light induced fluorescence (LIF), neutral gas metrology (flow meters, mass-spectrometry vacuum gauges), plasma module integrity health monitoring.

-) Beyond the state-of-the-art, two examples:
Ultra-sensitive, slow (~ 10 Hz), SHDI;
Ultra-fast time-domain 2D SHDI.

-) Some suggested topic for discussion

WP10 - Diagnostics

WP10 GOAL

Define a road-map for HRR plasma components development and deployment in a high-quality plasma accelerator, *including diagnostics tools*;

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-) The d*eployability* is a necessary condition for integration in the plasma component within the beam line (related also to plasma component diagnostics integrity/health).

Stability-reproducibility in a plasma-based accelerator

i) D*river pulse reproducibility* - more critical when substantial ionization is generated by the driving pulse itself, like in laser-driven;

ii) *plasma stability* - higher in “slowly” hydro-dynamically evolving pre-plasma, lower in laser-plasma due to fluctuations in the drive pulse and neutral particle density;

Actions:

a) higher level of stabilization of the driver pulse – mandatory for laser-driven, [Implementation of a single-shot metrology system for a TW-class laser in a particle accelerator facility, Optics & Laser Technology, 180, 111523 (2025)];

b) optimize plasma modules stability, and accurately monitor the neutral gas density/geometry and its fluctuations;

c) Bayesian optimization: collective analysis of on-line driver pulse and *plasma modules* diagnostics → counter-actions on driving-pulse and plasma modules to optimize a beam parameter.

d) HRR and burst operation can mitigate the effect of process instabilities (ultra-fast, extreme gradients, non-linearity);

Density in EuPRAXIA plasma modules

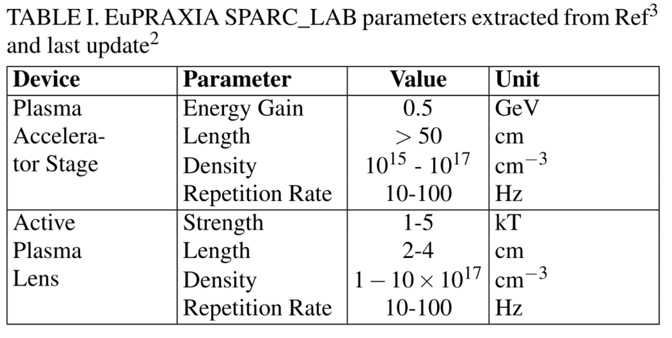


TABLE I. EuPRAXIA SPARC_LAB parameters extracted from Ref[3] and last update[2]

Device	Parameter	Value	Unit
Plasma Accelerator Stage	Energy Gain	0.5	GeV
	Length	> 50	cm
	Density	10^{15} - 10^{17}	cm^{-3}
	Repetition Rate	10-100	Hz
Active Plasma Lens	Strength	1-5	kT
	Length	2-4	cm
	Density	$1 - 10 \times 10^{17}$	cm^{-3}
	Repetition Rate	10-100	Hz

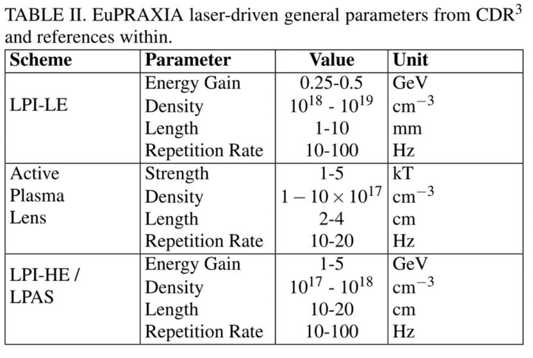
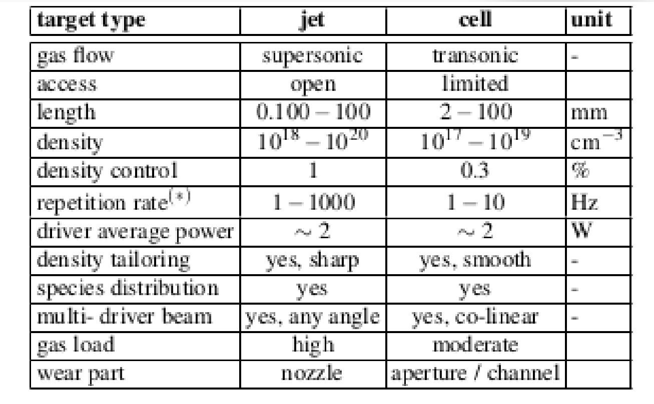


TABLE II. EuPRAXIA laser-driven general parameters from CDR[3] and references within.

Scheme	Parameter	Value	Unit
LPI-LE	Energy Gain	0.25-0.5	GeV
	Density	10^{18} - 10^{19}	cm^{-3}
	Length	1-10	mm
	Repetition Rate	10-100	Hz
Active Plasma Lens	Strength	1-5	kT
	Density	$1 - 10 \times 10^{17}$	cm^{-3}
	Length	2-4	cm
	Repetition Rate	10-20	Hz
LPI-HE / LPAS	Energy Gain	1-5	GeV
	Density	10^{17} - 10^{18}	cm^{-3}
	Length	10-20	cm
	Repetition Rate	10-100	Hz



target type	jet	cell	unit
gas flow	supersonic	transonic	-
access	open	limited	
length	$0.100 - 100$	$2 - 100$	mm
density	$10^{18} - 10^{20}$	$10^{17} - 10^{19}$	cm^{-3}
density control	1	0.3	%
repetition rate$^{(*)}$	$1 - 1000$	$1 - 10$	Hz
driver average power	~ 2	~ 2	W
density tailoring	yes, sharp	yes, smooth	-
species distribution	yes	yes	-
multi- driver beam	yes, any angle	yes, co-linear	-
gas load	high	moderate	
wear part	nozzle	aperture / channel	

Diagnostics for Density measurements:

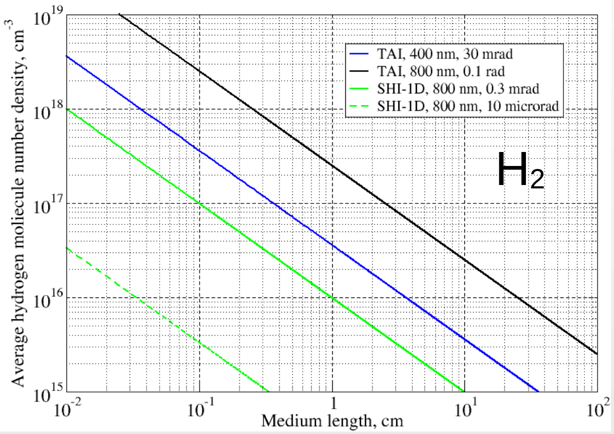
The average plasma density value (range) for each plasma module design is associated with a ***stability*** *level requirements; uniformity in space should also be specified.*

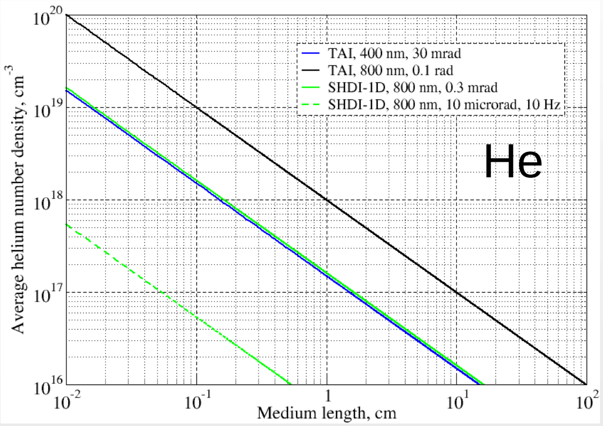
→

these quantities (together with the actual geometrical design in terms of plasma dimensions, including transversal, and optical accesses) dictates the decision of the best diagnostics tools possible to monitor the plasma module.

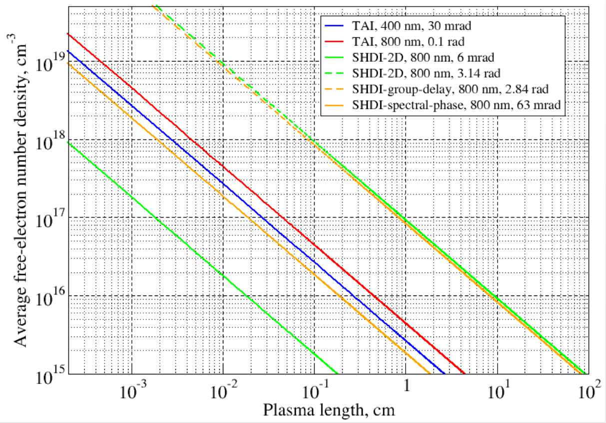
The road-map should include an indication of the density stability/homogeneity required for each Plasma Module, and highlight the need for further R&D in diagnostics beyond the state-of-the-art when needed.

Interferometric capabilities





Free-electrons (non rel.)



-) *Spatial TAI (finite-fringe width)* – Phase$_{min}$=2π/(#pixels-per-fringe) ~ tens of mrad detection baseline, multi-pass approaches "lengthen" the medium to increase S/N and overcome the baseline limitation - for test and optimization of plasma modules;

-) *Wavefront sensor*, single arm – Phase$_{min}$ ~ 30 mrad (commercial product specs) - on-line deployment;

-) 2D-*SHDI (infinite-fringe width),* single arm – Phase$_{min}$ ~ 6 mrad - on-line deployment, [Opt. Lett. 45, 4304 (2020), room for improvement to the ~mrad]

-) *Time-domain SHDI,* single arm – Phase$_{min}$ ~ 0.3 mrad - on-line deployment;[Opt. Lett. 32, 2327 (2007), room for improvement to the microrad level]

-) *Spectral-domain SHDI,* single arm – Phase$_{min}$ ~ 60 mrad - test and optimization [Phys. Plasmas 26, 023106 (2019)]

Diagnostics +

-) *Plasma optical emission spectroscopy – pressure broadening (test, and operation)*

On-line deployable (?), transparent materials; Sensitivity: what is affecting it and how to improove; Accuracy: need calibration (10%)? – need proper gas.

(Question: is plasma *temperature* measurement feasible, eventually in combination with others diags?)

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Provide a visual information on density dis-homogeneity (turbulence).

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Wide field and high resolution optical imaging (e.g., nozzle/cell orifice/capillary damages);

Thermal imaging (other plasma module temperature sensors?).

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-) *Neutral gas flow metrology* (operation)

Flowmeters in continuous flowing gas supply system;

Vacuum gauge with mass spectrometry (to monitor *gas mixtures stability* and vacuum contaminants).

Examples of R&D

1) Ultra-sensitive SHDI

GOAL: Slow time-domain measurement (BW~10 Hz) at the *microrad* level

→

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2) Ultra-fast 2D-SHDI

GOAL: High-sensitivity (~*mrad*) time-domain measurement of plasma density distribution with ultra-short pulses

→

need R&D to test group velocity delay control, and the use of broadband optics

Enables to make accurate ultra-fast measurement of average densities < 10^{16} cm^{-3} for a ~100 micrometer plasma, preliminary R&D foreseen @ILIL lab

More on R&D for Diagnostics

-) There are commercial companies and on going scientific collaboration for the development of new plasma modules.

-) Concerning diagnostics development, deployment, and integration, *the R&D collaborative efforts should be increased*.

Take home messages:

1) standardization: define a commonly agreed diagnostics portfolio, to allow for a better comparison between various experiments exploring different schemes.

2) specific R&D program in plasma module diagnostics, also in collaboration with SME, are desirable to push forward scientific collaboration and commercial product development.

”Power is nothing without Control …”

Some topic for discussion

- Diagnostics readiness (TRL?):

  -) Wavefront-based diag.: *commercial product available (TRL 9)*;

  -) Pressure broadening spectrometers are routinely used in experiments also in large facilities; are commercial products suitable for plasma accelerators facility available? (TRL ?)

  -) The SHDI, is becoming the new standard for density plasma characterization in large plasma private and public facilities, also ITER, integrating/replacing two-color and far-infrared interferometer (TRL 5-6?); *R&D is needed to fully leverage the SHDI exceptional stability and sensitivity within plasma accelerators*.

- Given the reported success in implementing Bayesian Optimization, *are there specific metrology needs (new/improved?) for its implementation in an accelerator facility?*

- Is a specific *on-line diagnostics for the plasma wave* needed? (can it support in the matching/synchronization between successive stages?)

Topic for discussion: turbulence

- There are experimental evidence that a mitigation in the turbulence in the neutral gas flow correlates with a better stability of the accelerator.
- Can the effect of turbulence in the gas target be included in the 3D plasma acceleration simulations? (i.e., include directly either the result of 3D CFD simulation or include random density fluctuations with specific dimensions and depth distribution resulting from CFD …)
- It would be very beneficial for diagnostics definition and further development to address the turbulence issue answering the question:

  what is the maximum acceptable level of turbulence in the density distribution of a plasma module (e.g., in terms of localized density variation and their size distribution …)?