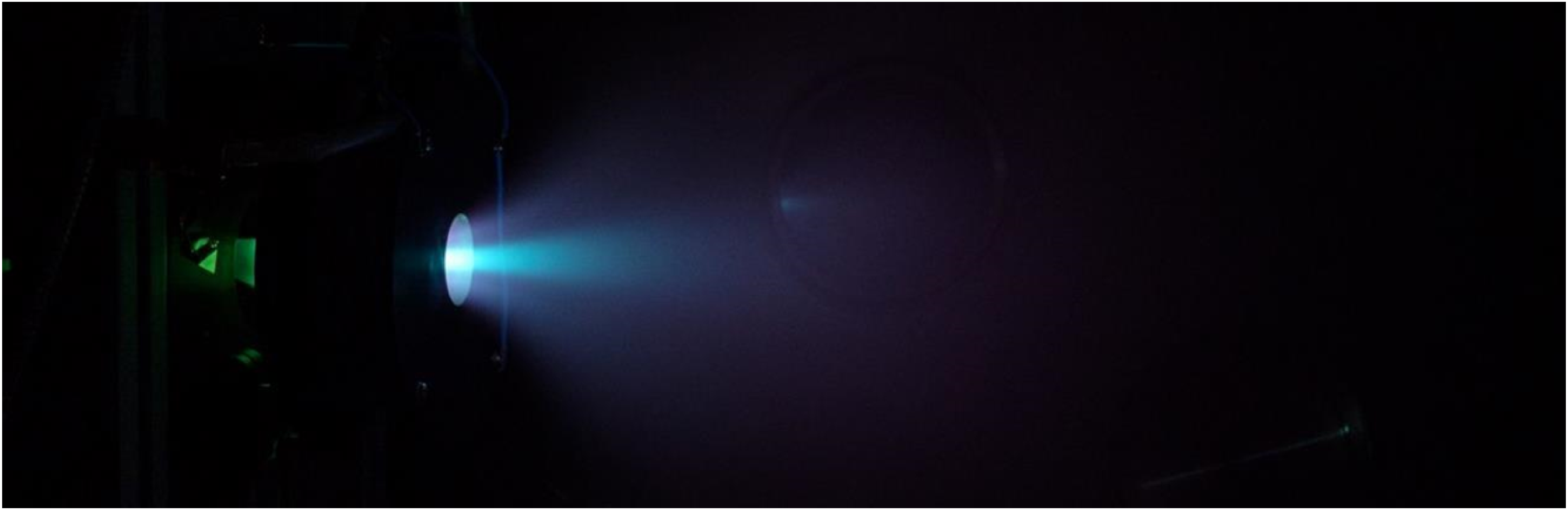
DTK
Diagnosis ToolKit for Plasma Thrusters

SENER Aeroespacial · uc3m · EP2 · cnrs · ICARE

Final Presentation, VC. 30th November 2022.

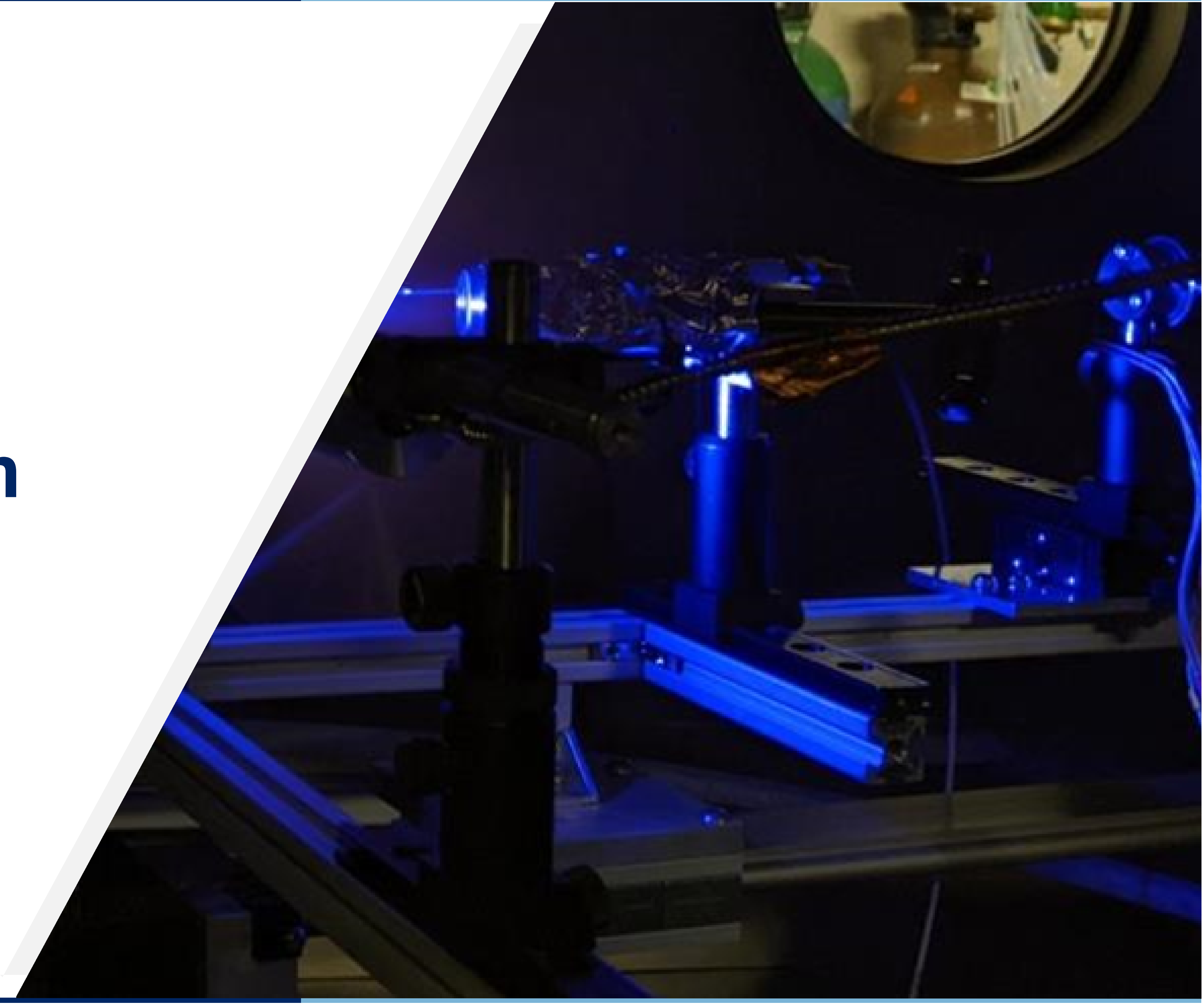


Diagnosis Toolkit for Plasma Thrusters
Final Presentation

DTK Final Presentation
Agenda

- 15:00-15:10 → Introduction
- 15:10-15:40 → Summary of Design and Development tasks
- 15:40-15:10 → Summary of Performance Verification tasks
- 15:10-15:30 → Results assessment and open discussion
- AoB and closure.

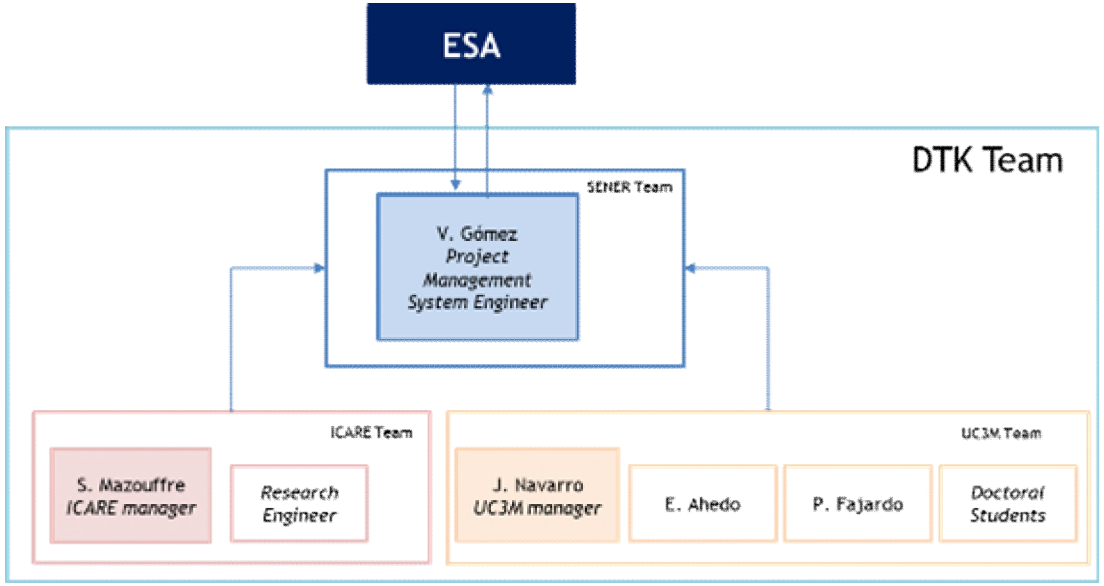
Introduction



Introduction

The team

SENER	UC3M	CNRS
 Mercedes Ruiz	 Jaume Navarro-Cavallé	 Stéphane Mazouffre
	 Marco Inchingolo	 Quentin Delavière
	 Eduardo Ahedo	 Alfio Vinci



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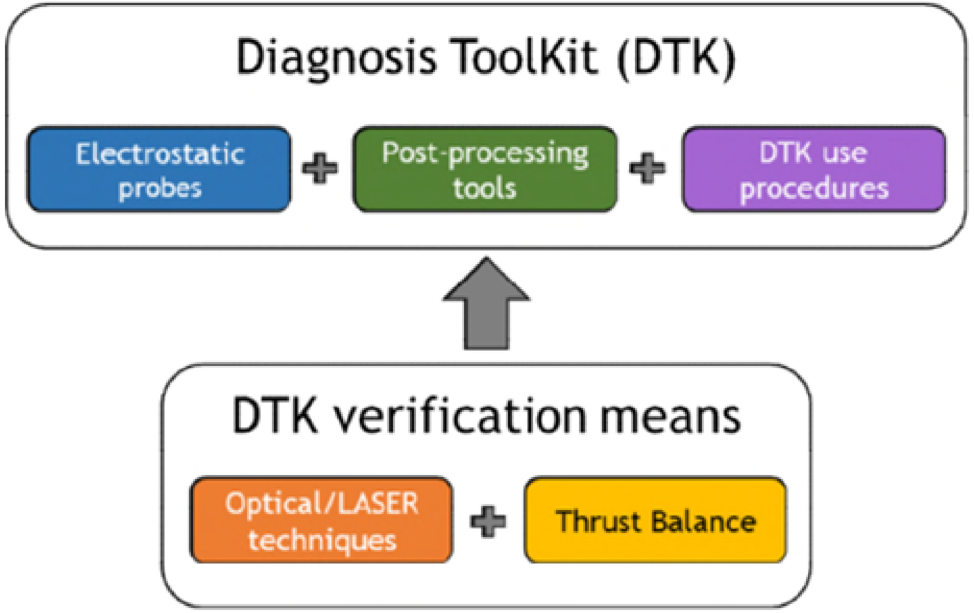
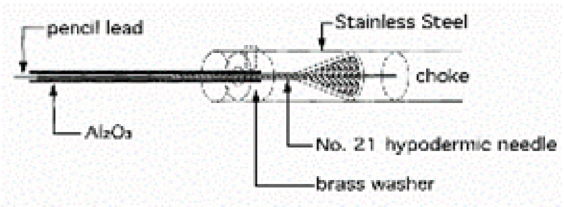
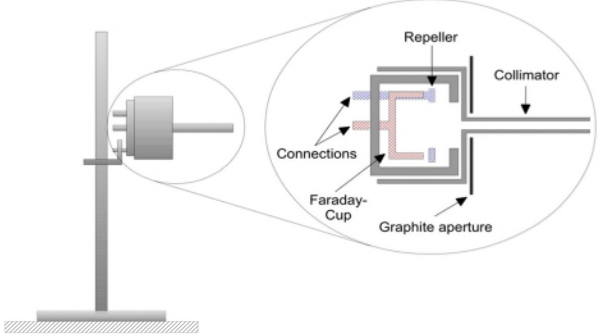
Diagnosis ToolKit for Plasma Thrusters

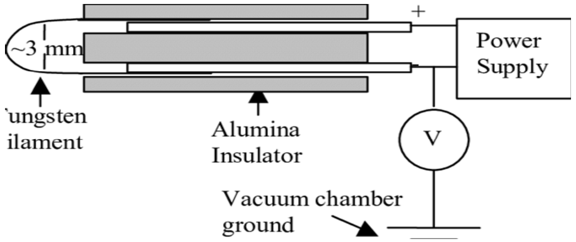
Introduction
Project Goal

The goal of the project is to develop, integrate and validate a Diagnosis ToolKit (DTK) that improves the measurement performance of currently available diagnosis systems for Plasma Thrusters.





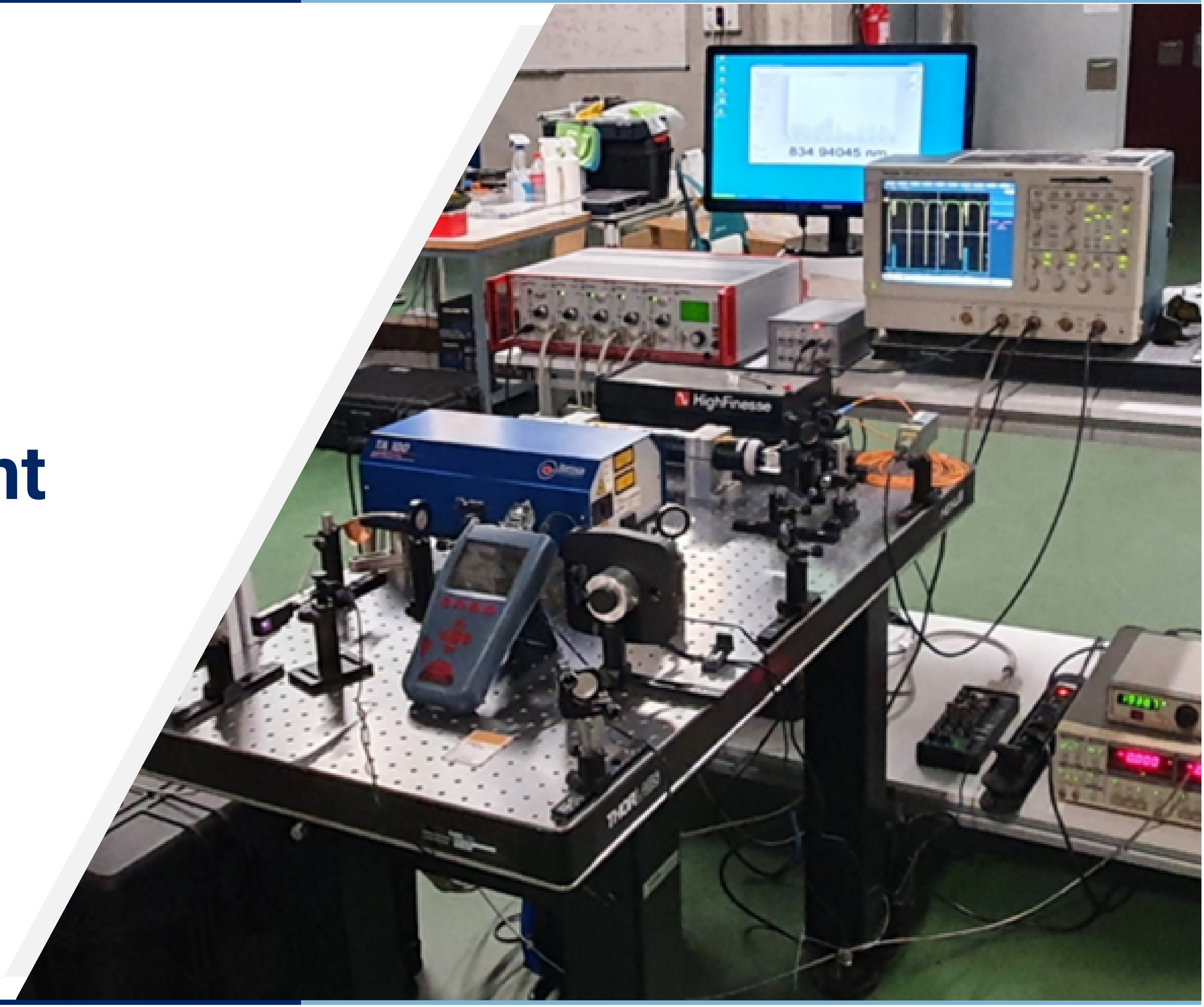




Introduction
Schedule and progress

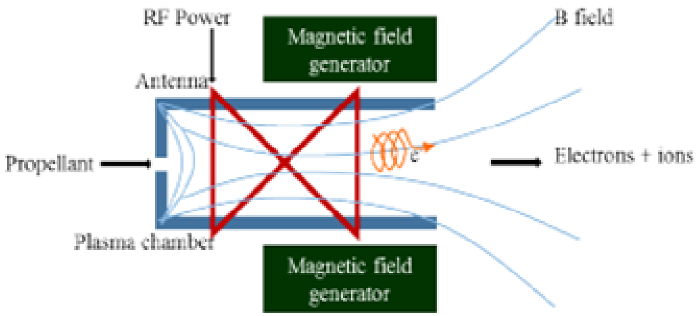
ID	Title	Periodicity/ Milestone	Format	Deliver to	Due Month	Delivered
MoM	Minutes of Meeting (including updated Bar-chart)	As required	pdf	TO, CO	-	-
PR	Progress Report	monthly	pdf	TO	-	-
D1	State-of-Art Assessment of Plasma Thrusters and Applicable Plasma Diagnostics	SoA&CR	pdf, docx	TO	jun-21	Yes
D2	Plasma Diagnostics Selection and Conceptual Design	SoA&CR	pdf, docx	TO	jun-21	Yes
D3	Plasma Diagnostics Technical Requirements Document	RR	pdf, docx	TO	sep-21	Yes
D4	Plasma Diagnostics Design Report	DR	pdf, docx	TO	nov-21	Yes
D5.1	Plasma Diagnostics Performance Tests - Specification and Procedures	DR (first version)	pdf, docx	TO	nov-21	Yes
D5.2	Plasma Diagnostics Performance Tests - Specification and Procedures	TRR (consolidated)	pdf, docx	TO	jun-22	Yes
D6	Plasma Diagnostics Performance Test Report	TRB	pdf, docx	TO	oct-22	Yes
TDP	Technical Data Package (D1 to D6, PRs and MoMs)	FR	pdf, docx	TO	dec-22	No
AB	Abstract	FR	pdf	TO	dec-22	No
TAS	Technology Achievement Summary (using TAS template)	FR	pdf, docx	TO	dec-22	No
FP	Final Presentation	FR	pdf, docx		dec-22	No
ESR	Executive Summary Report	FR	pdf, docx	TO, CO, ESA I&D Centre	dec-22	No
FR	Final Report	FR	pdf, docx	TO, CO, ESA I&D Centre	dec-22	No
CCD	Contract Closure Documentation	Contract closure	pdf	TO, CO	dec-22	No

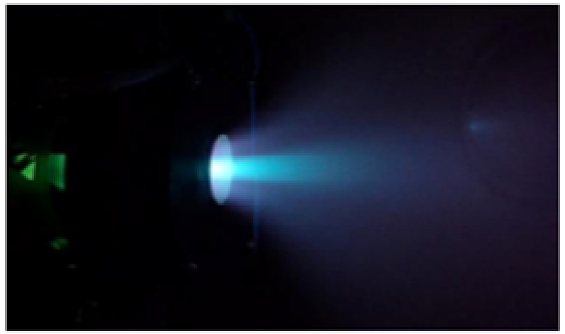
Design and development tasks



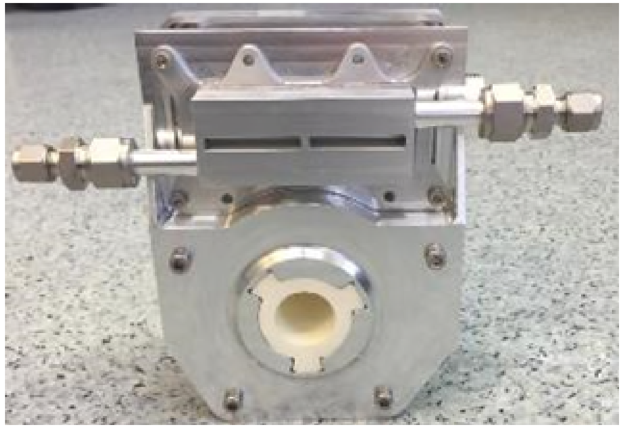
Summary of Design and Development tasks

The thruster prototypes





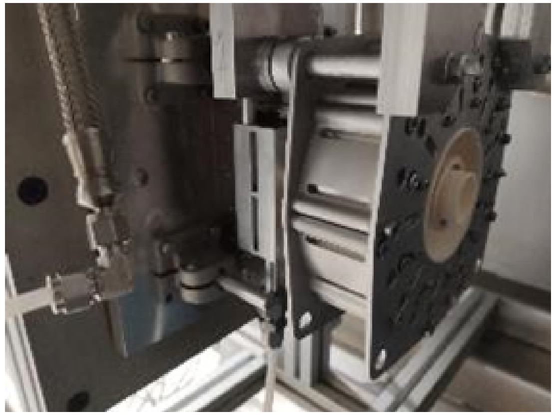
HPT-05M EBBM



HPT EM

“Gandalf” EBBM

“Lavadora” EBBM



HPT-03 EBBM

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Summary of Design and Development tasks

RFCLP & FC Design - Introduction

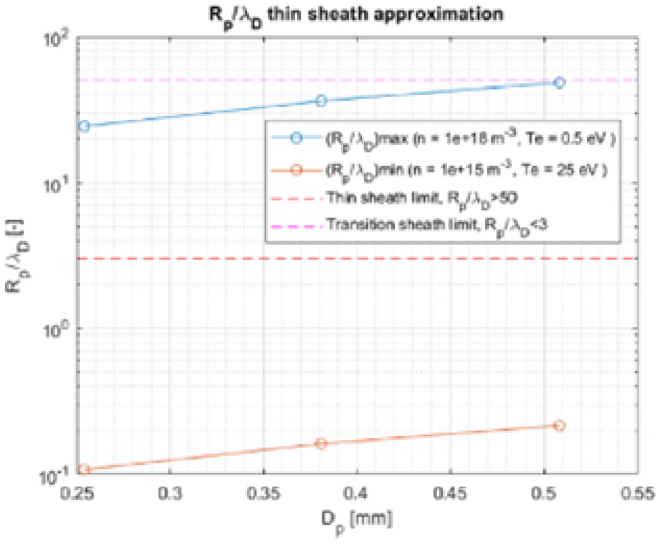
- The **state of the art** of RFCLP and FC was reviewed at the beginning of the DTK project: DTK-UC3M-TN-001. Some incipient ideas arising from the review:
- For **RFCLP** is recommended to operate within the range of validity of the LP theory used to postprocess the IV curve. This suggests to *design several tip probe geometries to accommodate the large gradients of some plasma properties along the plasma plume of a PT*.
- For the **FC** the modular design would bring us a *testbed to analyze different effects*: vented/not-vented probe, aperture/collimator ion optic effects, SEE, etc., and increase the *understanding* of the results disagreement between existing FC/FP probes.

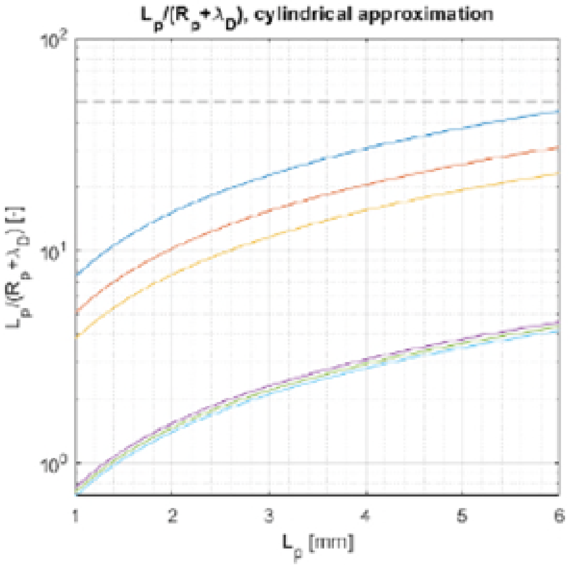
- **Technical requirements** were derived for both probes, the probe assembly and postprocessing tools: DTK-UC3M-TN02.

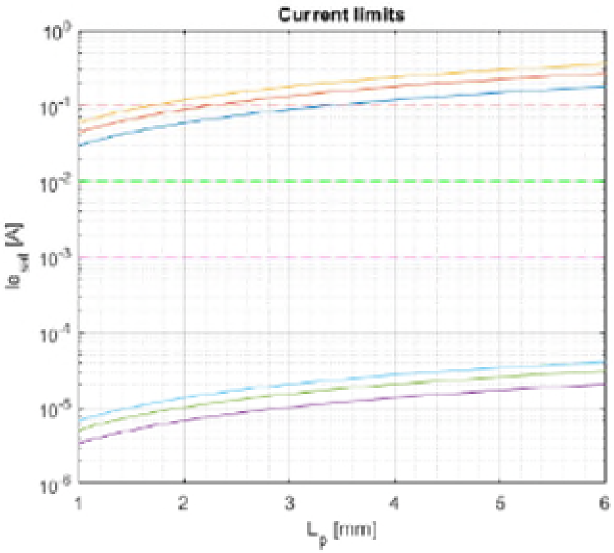
Summary of Design and Development tasks

RFCLP Design - Justification

- Thin sheath cannot be reached with the limit plasma conditions.
- Be compliant with the cylindrical approach, longer lengths might help with the cylindrical approximation in the far field.
- Account for the current limits of the DAQ.







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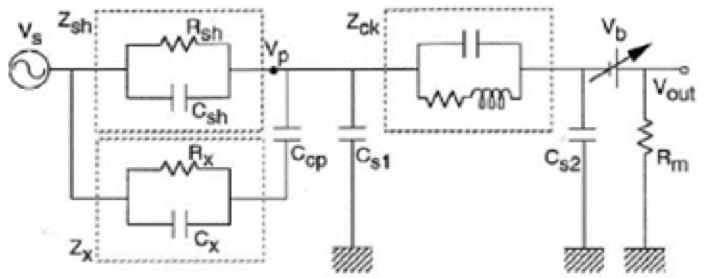
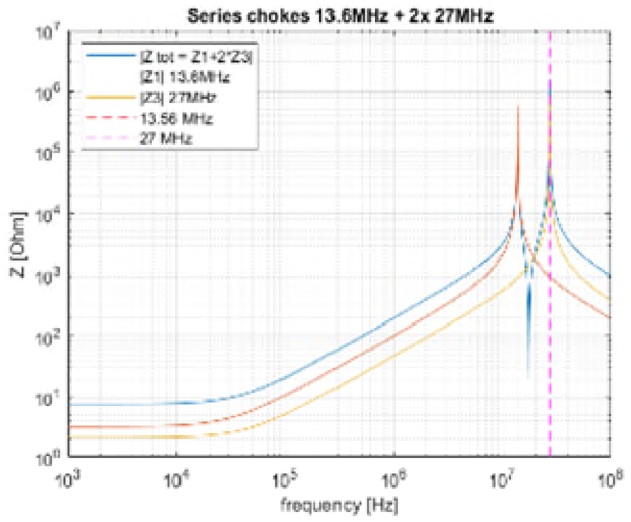
Summary of Design and Development tasks

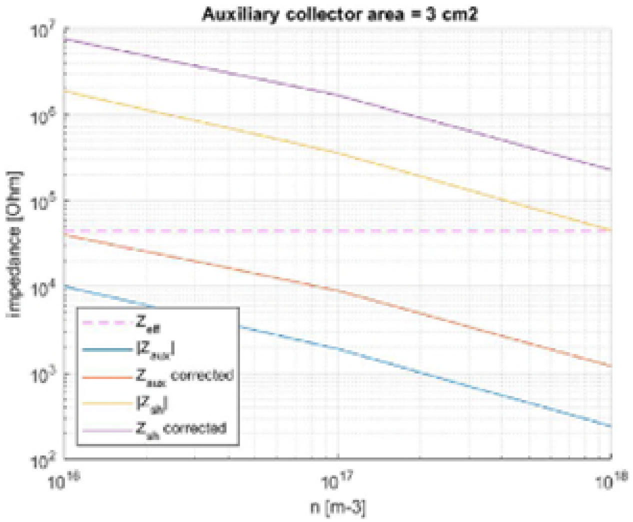
RFCLP Design - Justification

- RF compensation [Chen model].
- Two harmonics RF compensation
  - 13.5 MHz
  - 27 MHz
- Minimum area to satisfy the impedance requirement A = 3cm2

$$Z_{eff} \gg Z_{sh,x}\left(\frac{e|V_{rf}|}{K_b T_e} - 1\right)$$







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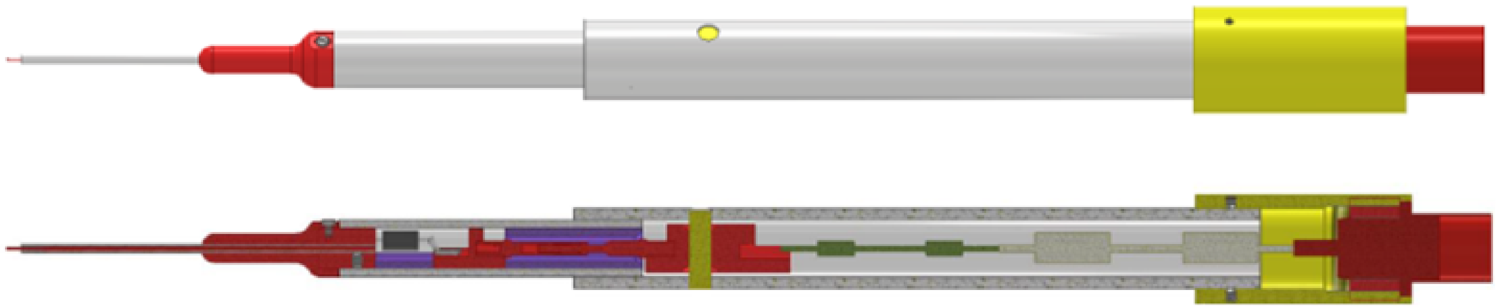
Summary of Design and Development tasks

RFCLP - Modular design

- Modular approach
  - No Zirconium paste used, components completely replaceable
- Easy replace of probe tip assembly
- Classical telescopic design



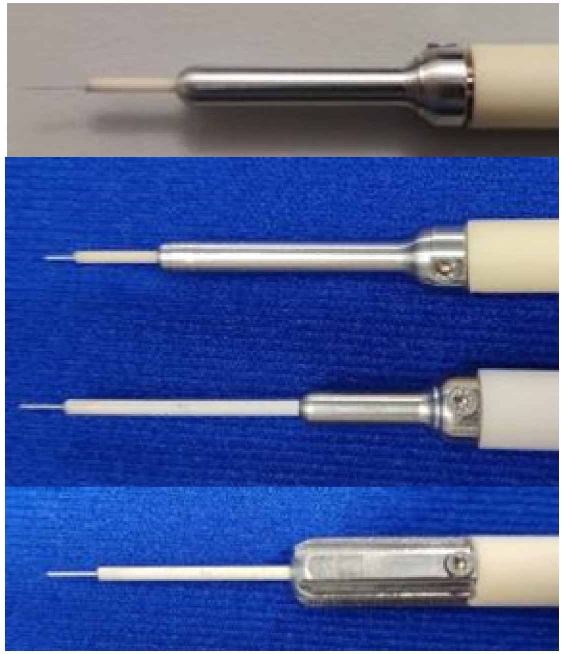
#	Dp [mm]	Lp [mm]	A [cm2]	Plume location
1	0.254	2	3, 4, 6	Close field
2	0.254	3	3, 4, 6	Close field
3	0.254	4	3, 4, 6	Far field
4	0.254	6	3, 4, 6	Far field
5	0.381	6	3, 6	Far field

Summary of Design and Development tasks

RFCLP – Manufacturing & Integration

- More than 4 different tips have been manufactured (only 4 will be tested): length, thickness, surface of the secondary electrode.
- Main body with the same internal electronics. RF chokes at 13.5 MHz

Ref:	Description
LP1	L=6 mm; D=0.010 in (0.254 mm); medium size secondary electrode (4 cm^2).
LP2	L=3 mm; D=0.010 in (0.254 mm); medium size secondary electrode (4 cm^2).
LP3	L=6 mm; D=0.015 in (0.381 mm); small size secondary electrode (3 cm^2).
LP4	L=6 mm; D=0.015 in; large size secondary electrode (6 cm^2).



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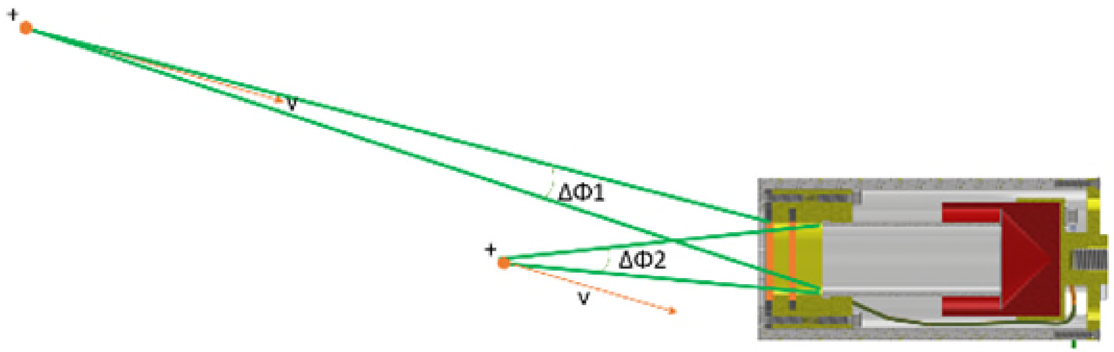
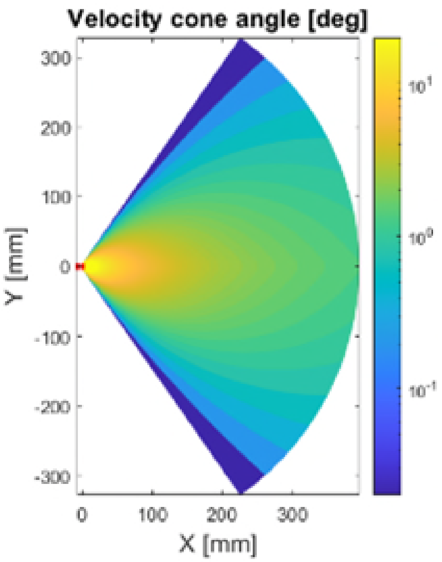
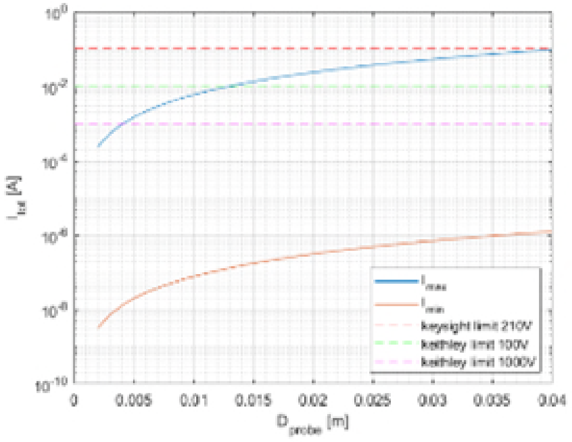
Summary of Design and Development tasks

FC Design - Justification

- Better use of materials and geometries.
- Separation of the front aperture and collimator in two components.
- Increased neutral particles evacuation area.
- Reduced SEE and its impact on the measurements.
- Account for the DAQ current limits, CL sheath size, etc.
- Geometrical consideration of the ion optics.



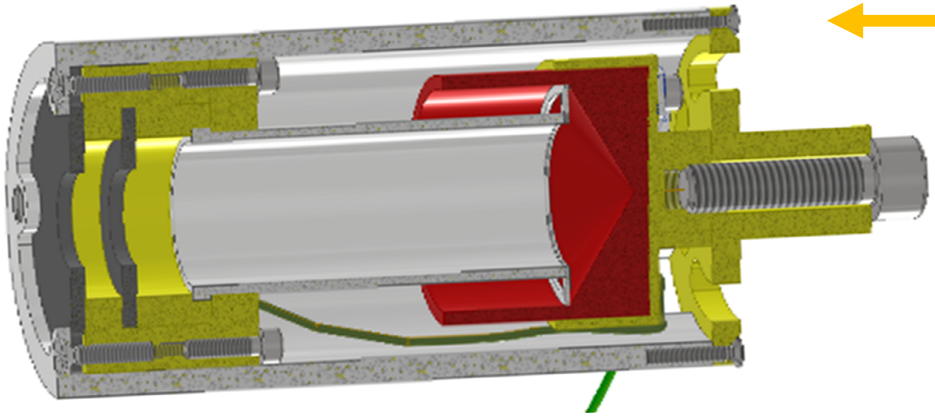


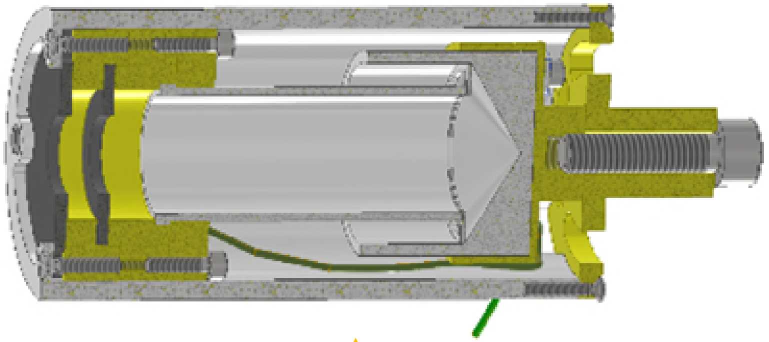


Summary of Design and Development tasks

FC Design - Modular Design

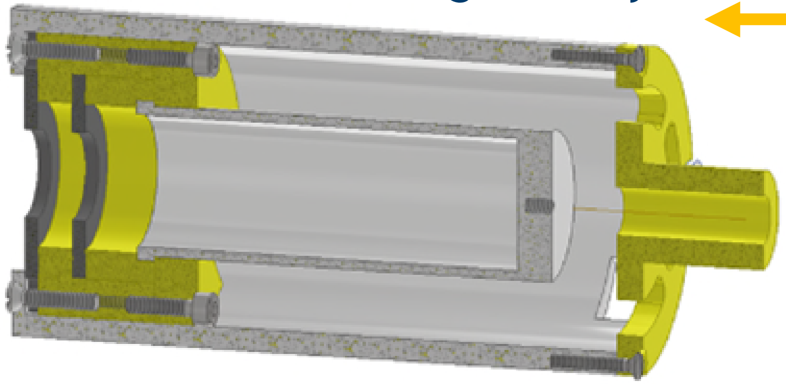
Effect of the collector material

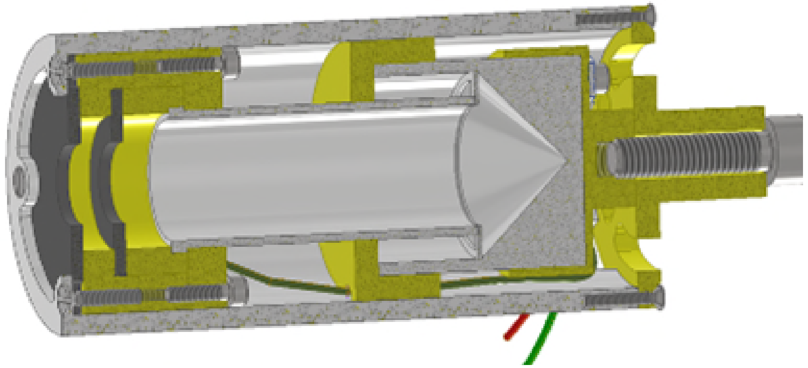




Effect of the increased neutral escape area.

Effect of the collector geometry



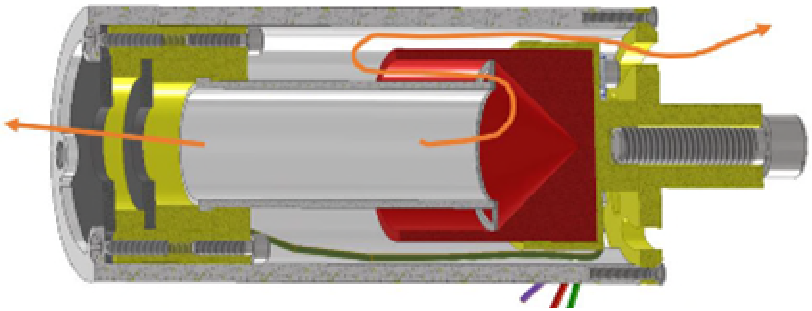


Summary of Design and Development tasks

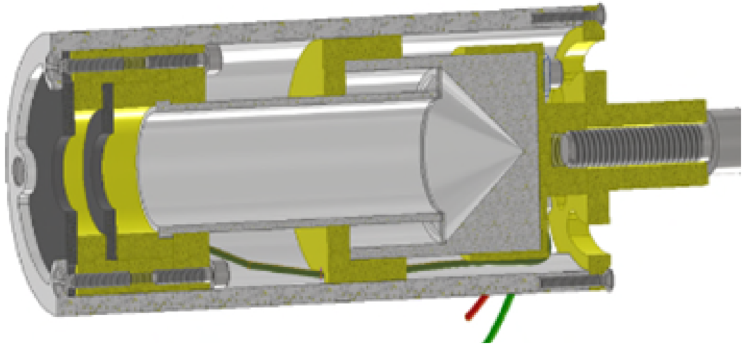
FC – Manufacturing & Integration

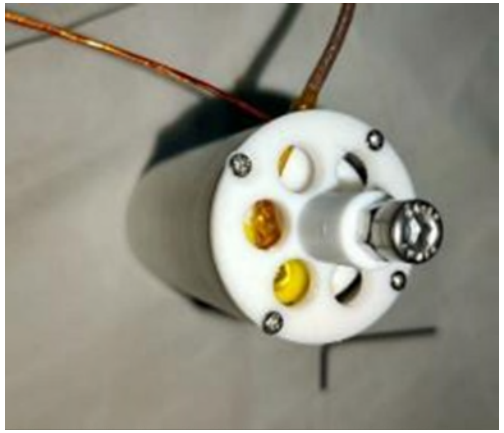
- Two different configurations have been tested:
  - **Vented**
  - **Not-vented**
- Aperture and collimator are independent electrodes.
- Same aperture diameter (10 mm) as former FC-ep2, FP-ep2.

vented



Not vented





Summary of Design and Development tasks

Retarding Potential Analyzer and Laser-induced fluorescence spectroscopy

- Task 3 - WP2100: SoA review, assessment and trade-offs - focus on RPA and LIF
  - Definition of basic idea for RPA and LIF measurements
  - Gathering quantitative guidelines for designing RPA and LIF systems
  - Qualitative definition of raw data analysis
  - Reporting a few implementation instances
  - Lessons learned from previous experiments at ICARE
  - Result: an extensive summary of useful inputs for following WPs
- Task 4 - WP2200 & 2300 & 2400:
  - RPA and LIF conceptual design
  - RPA and LIF performance, interface, mounting requirements
  - RPA design and LIF adaptation

Summary of Design and Development tasks

Retarding Potential Analyzer

Task 4 WP2000 – RPA Design considerations and Requirements

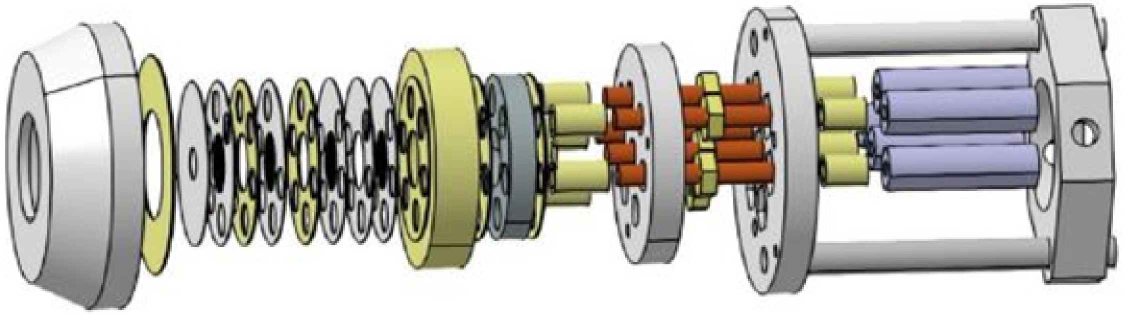
- Qualitative requirements:
  - *Ease of assembly* given a set of instructions and common tools
  - *Modularity* to easily replace malfunctioning parts
  - *Roustness* not to suffer from operation inside a plasma flux
- Quantitative aspects:
  - Grids aperture size set by local plasma sheath thickness
  - Grids spacing set by probe resolution and space-charge limited flow
  - Number of grids set by probe accuracy and volume constraints
  - Material selection set by thermal loads, SEE, outgassing, …

Summary of Design and Development tasks

Retarding Potential Analyzer

Task 5 WP2000 - RPA manufacturing and assembly

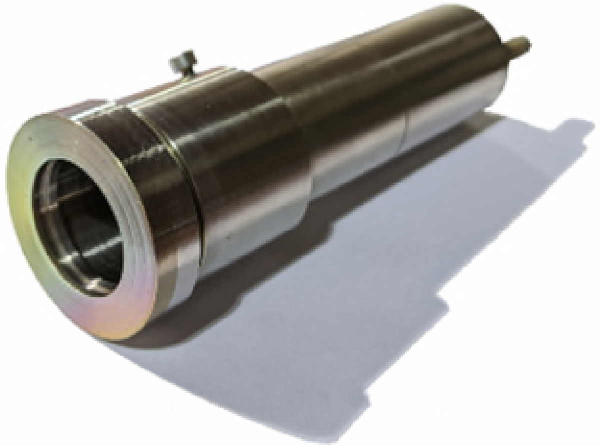
- Main body 26 mm OD x 11 mm height
- About 60 components in total
- 5 mm view port
- 4 or 5 grids (SS) with 0.15 mm holes and 25% transparency
- Alumina insulators for operation at relative high temperature



Summary of Design and Development tasks
Retarding Potential Analyzer
Task 5 WP2000 – LIF adaptation and assembly

- Optical fibres
  - Easy interfacing air-vacuum sides
  - multi-mode 50 µm for the excitation branch
  - multi-mode 200 µm core diameter for the detection branch

- Laser collimator
  - Custom 2-pieces aluminium case w/ SMA connector
  - aspheric lens (f = 8 mm, Ø = 10 mm)
  - 1/2" coated window for the 650 – 1050 nm range
  - Manually tunable to optimize beam size (typically 3-4 mm)



- Detection optics
  - Custom aluminum case w/ SMA connector
  - 1" biconvex f = 60 mm
  - Manually tunable length

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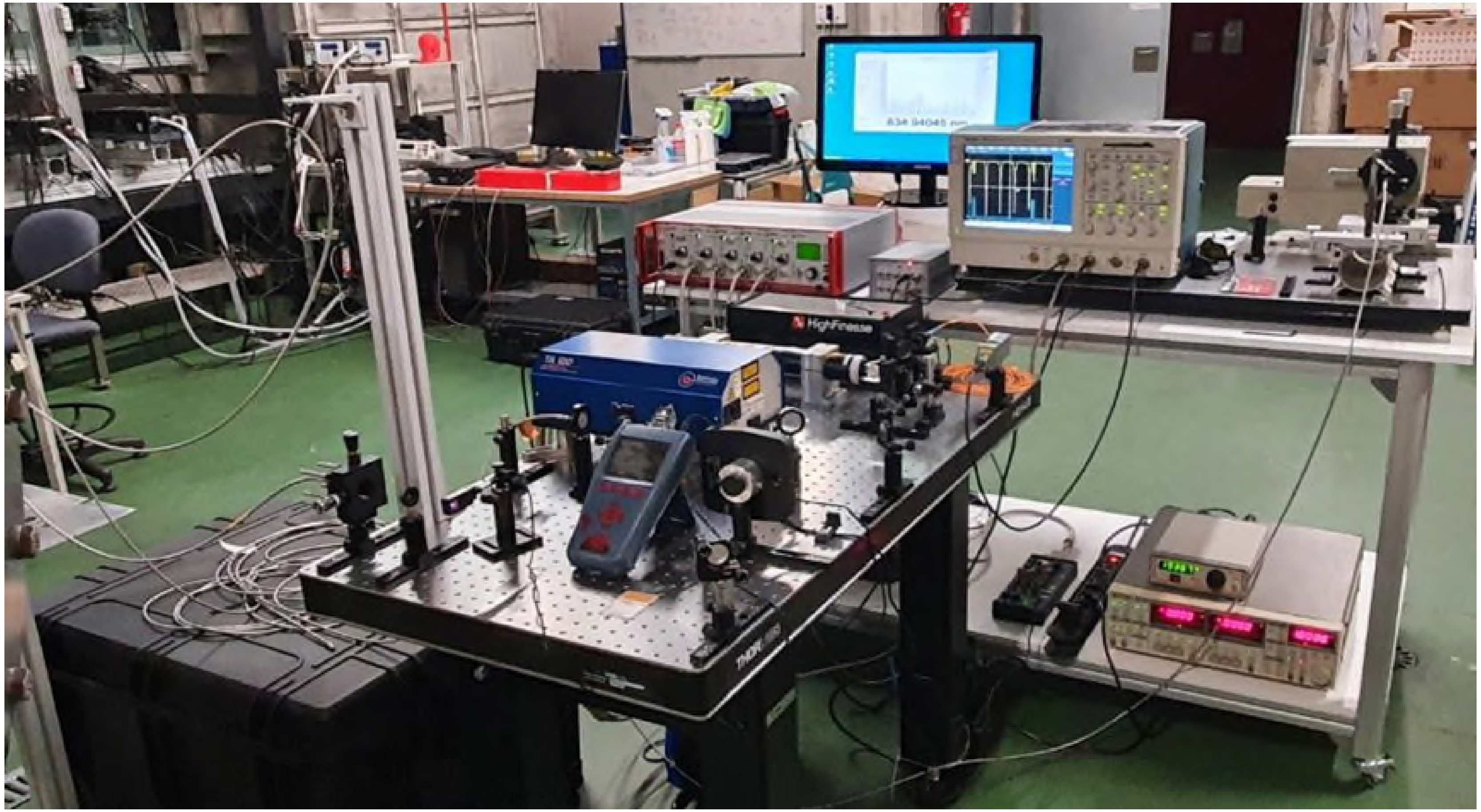
Summary of Design and Development tasks

Retarding Potential Analyzer

Task 5 WP2000 – LIF adaptation and assembly

- Laser diode
- Wavemeter
- Stabilised HeNe laser
- Fabry-Pérot
- Monochromator (filter)
- PMT
- Mechanical chopper
- Powermeter diode
- Fiber launcher



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Summary of Design and Development tasks

Post-processing tools - RFCLP, FC, RPA, DTK

Raw data file: P(x)-grid

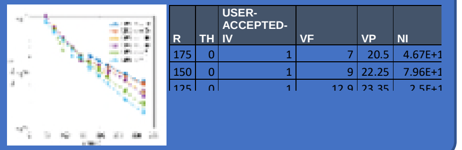
Postprocessing tool: RFCLP

Plasma Properties linked to R(x,y)

R	Th	ni	Te	Vp	…
R1	Th1	ni1	Te1	Vp1	…
R2	Th2	ni2	Te2	Vp2	…
…	…	…	…	…	…

Tool for reporting

Final Results:



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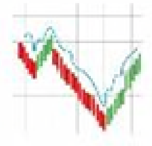
Results summary: P(x)-grid

Postprocessing plots: fittings, dI/dV, etc.



- Raw data file (probe / condition / position).
- Sequence (1/1/different position)
- Post-processing tool
- Reporting tool

Postprocessing tool: FC/RPA

DTK as a whole

DTK

Diagnosis ToolKit for Plasma Thrusters

Performance Verification tasks

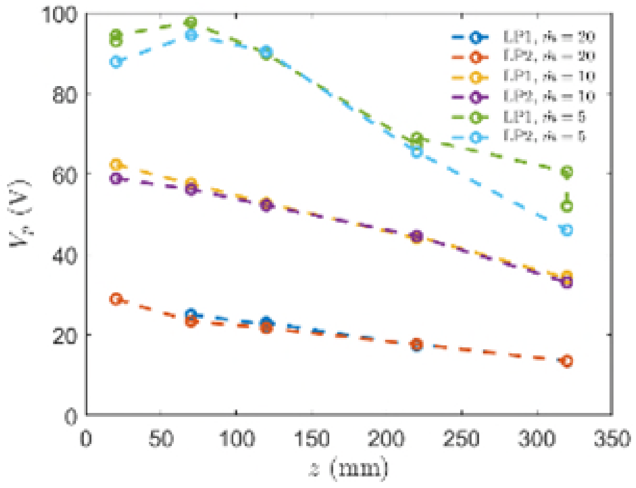
Summary of Performance Verification tasks

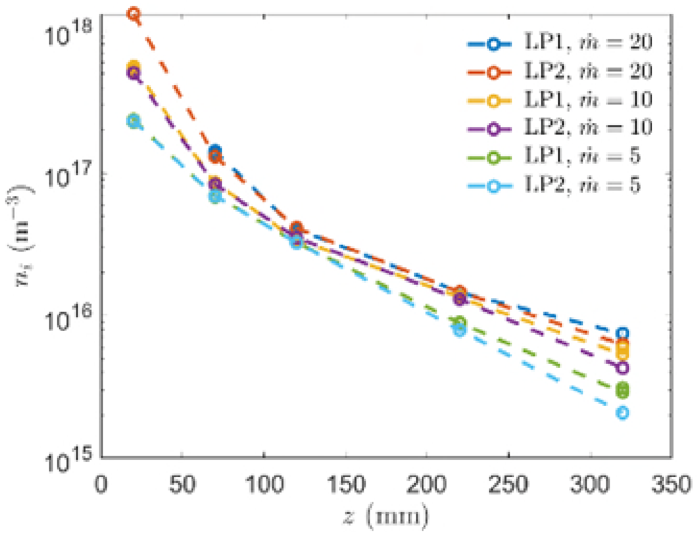
RFCLP Test

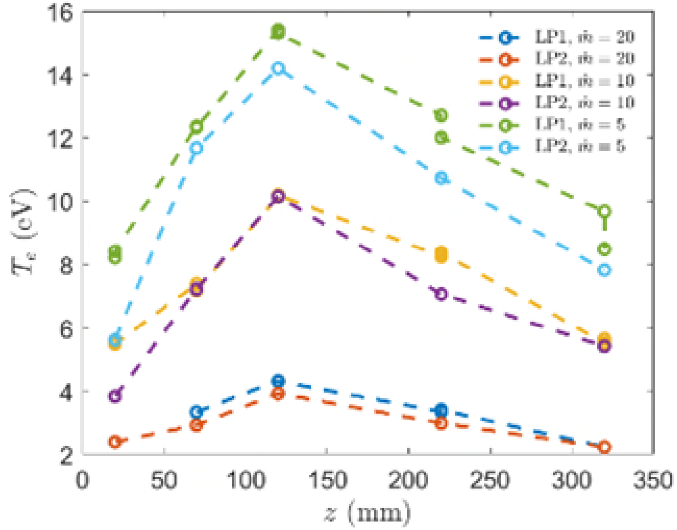
- Probes have been compared by pairs:
  - Pair 1: LP1 and LP2. Preliminary results (Sourcemeter → Keithley)
  - Pair 2: LP3 and LP2.
  - Pair 3: LP4 and LP2.
  - Pair 4: LP1 and LP2.
- Axial scan along the plume of the HPT05M prototype
  - 400 W RF, 13.56 MHz
  - 12 A → 650 Gauss (peak)
  - $\dot{m}_{Xe} = 5, 10, 20$ sccm
  - z = 20 – 320 mm (25 mm / 100 mm)
  - Distance between tips: 12 mm ; 6 mm off-axis.

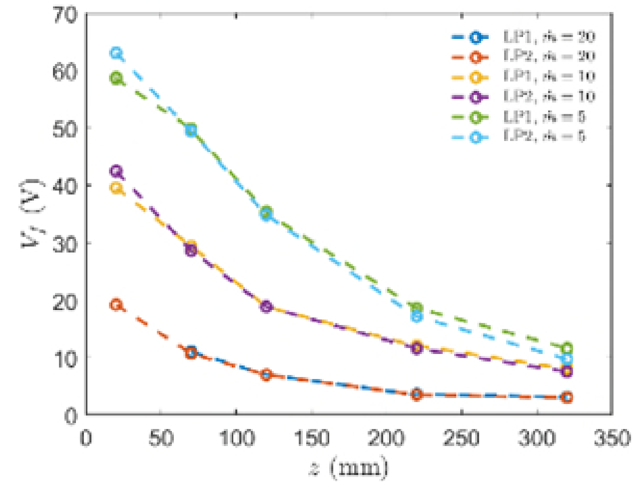
Summary of Performance Verification tasks

RFCLP example: LP1 – LP2 comparison







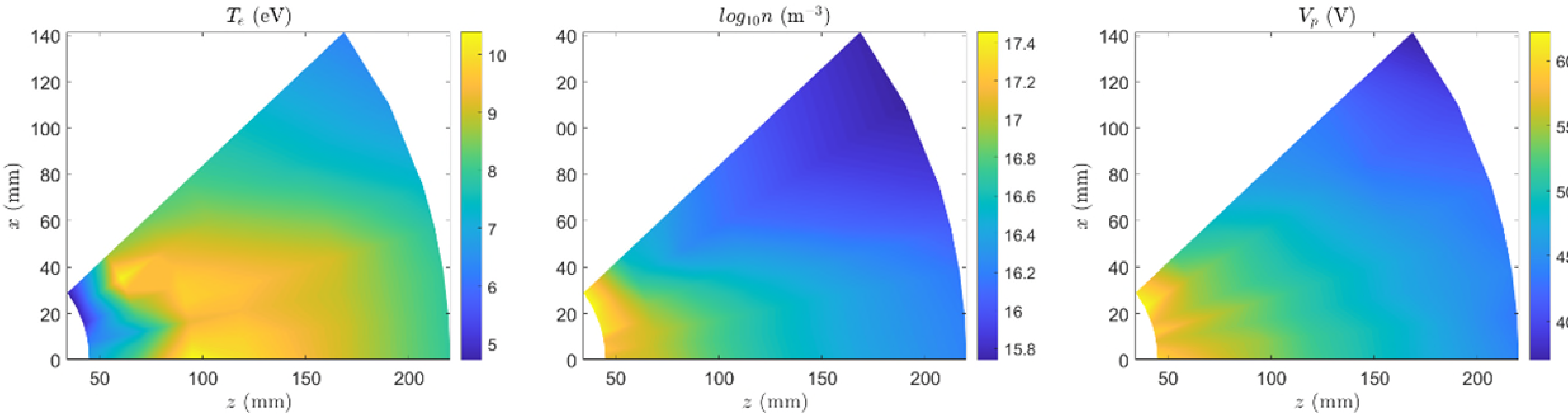


- Very Good overall trend, $n(\dot{m})$.
- At the close field, very good agreement between probes for the density (so plasma is symmetric), OML/transitional-cylindrical is valid for both probes in this range.
- n uncertainty at the mid-field / or complex expansion phenomena.
- Density estimation diverges at the far field (cylindrical OML theory should fail first for LP2, shorter rod).

Summary of Performance Verification tasks

2D MAPS: extended work from TRB

LP 4: temperature, density and Vp 2D maps.



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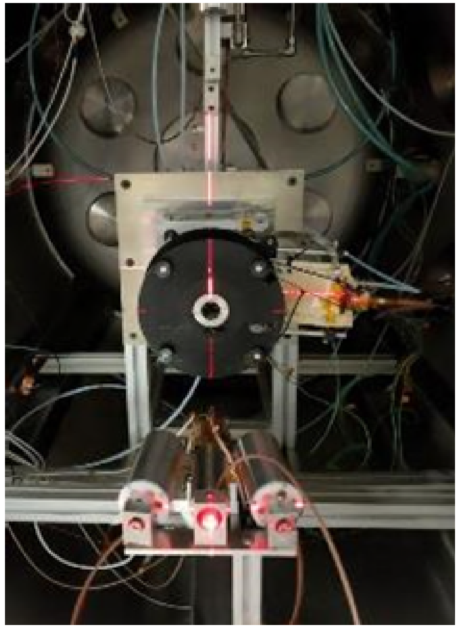
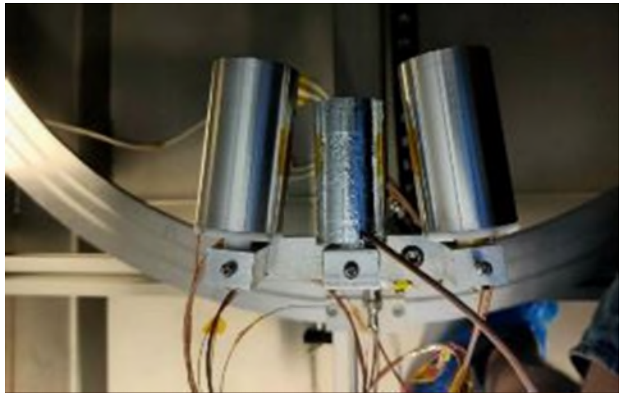
Summary of Performance Verification tasks

FC Test

- Possibility to test in the same plasma condition three probes at the same time.
- Laser alignment.
- Probes positioned at 400mm from the source on a polar rotating stage for performing plume scans.
- Same operating conditions of RFCLP tests.

Propellant	Mass flow rate (sccm)	Power delivered (W)	Coil current (A)
Xenon	5, 10, 20	400	12, 15

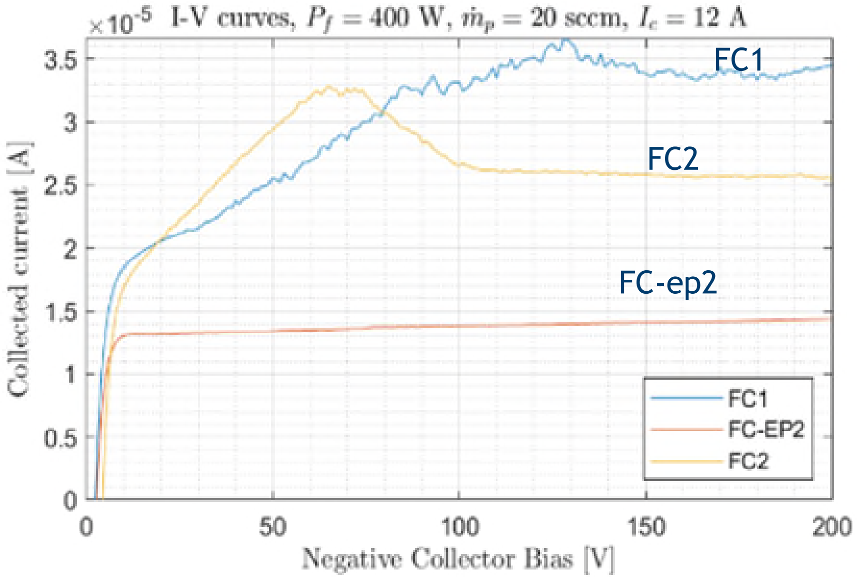


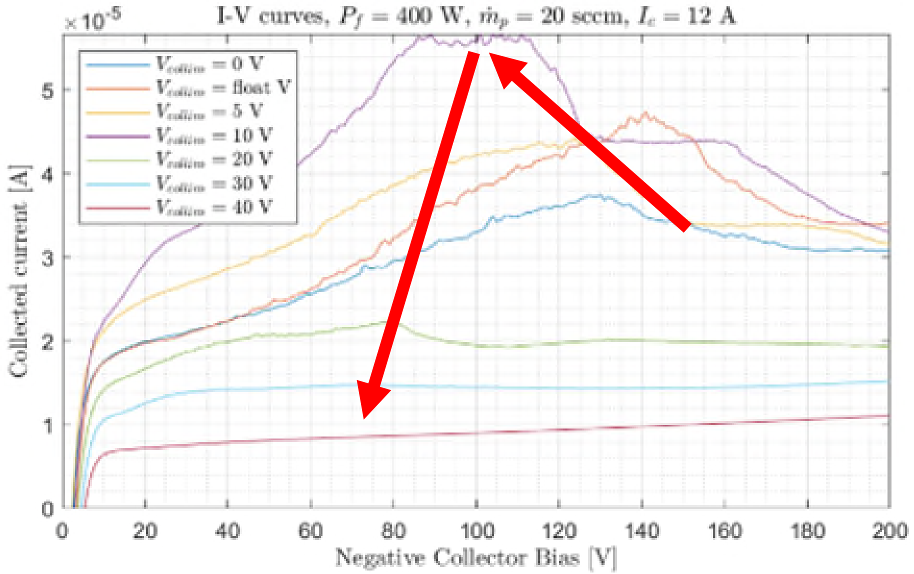


Summary of Performance Verification tasks

FC Results - IV example

- FC1 and FC2 show values in the **same order of magnitude** to each other. **Different behaviour depending on $\dot{m}$.**
- Ion optics were investigated by biasing the collimator.

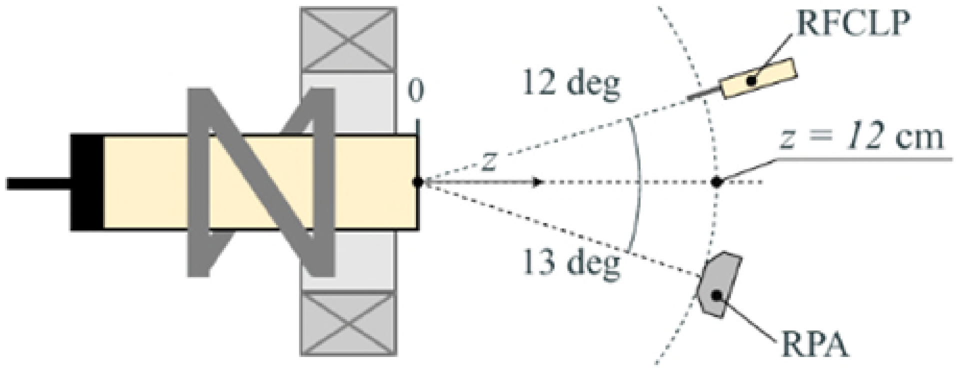


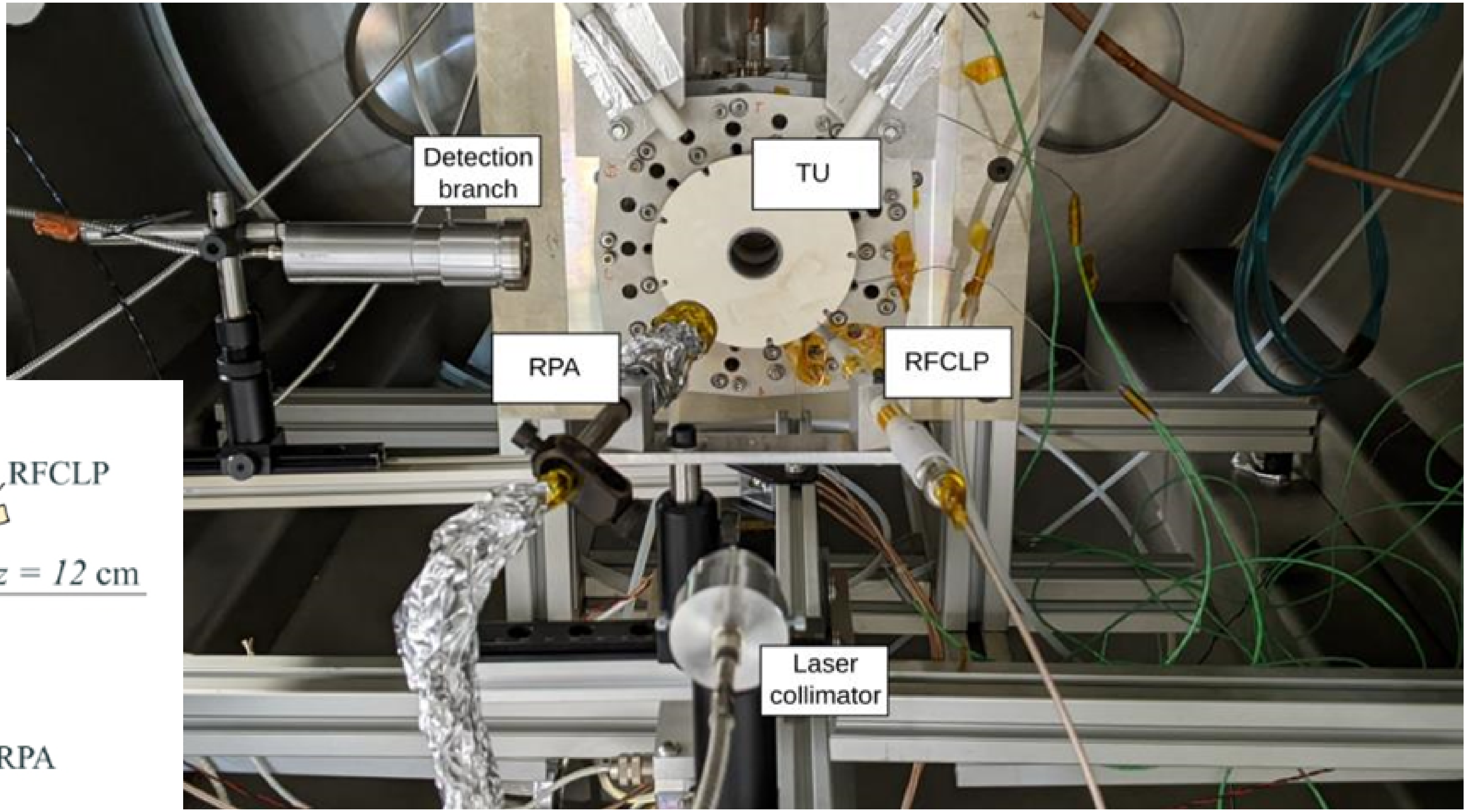


Summary of Performance Verification tasks

Retarding Potential Analyzer and Laser-induced fluorescence spectroscopy

Task 6 WP6000 - RPA vs. LIF measurements comparison



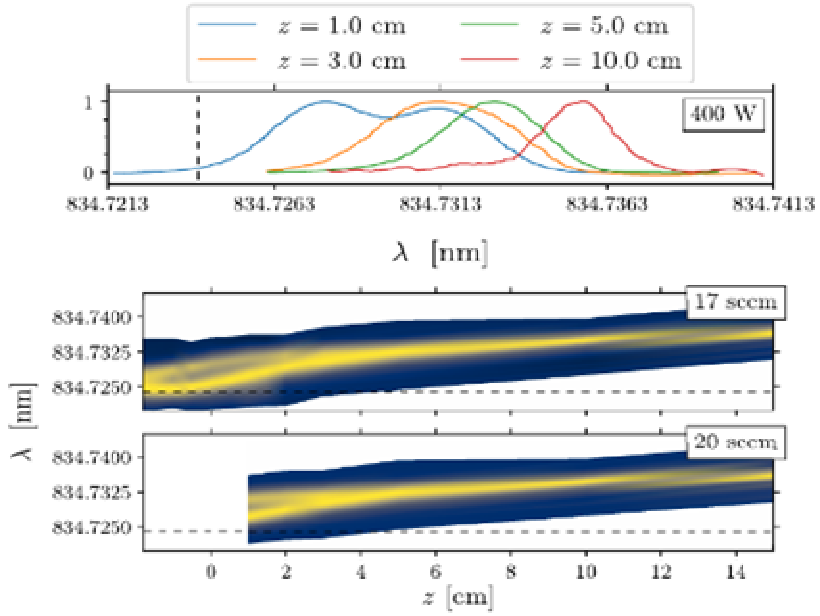


Summary of Performance Verification tasks

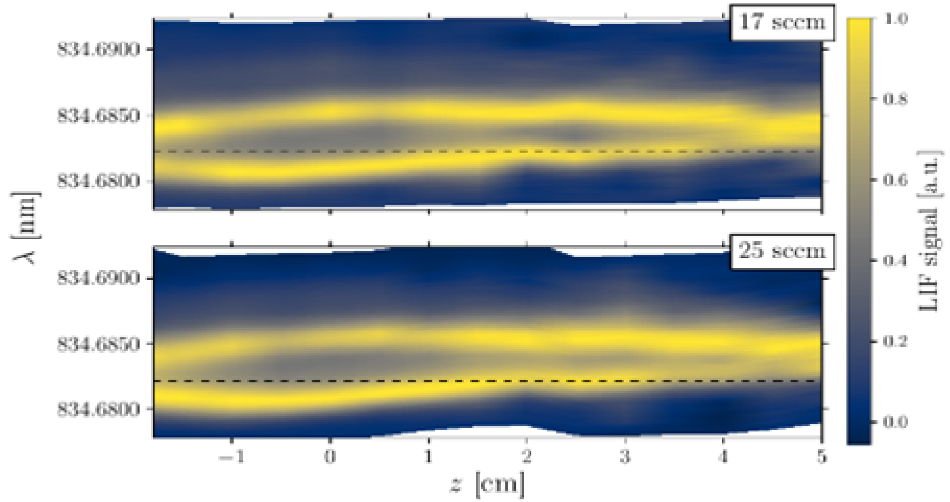
Retarding Potential Analyzer and Laser-induced fluorescence spectroscopy

Task 6 WP6000 - RPA vs. LIF measurements comparison

- Spectra exhibit double-peak shape close to z = 0 (both Xe I and Xe II)
- The double-peak cannot be linked to multiple populations, e.g. due to CEX collisions
- RPA vs. LIF comparison is unfeasible in the close-field plume



(a) LIF spectra of Xe II resolved along z

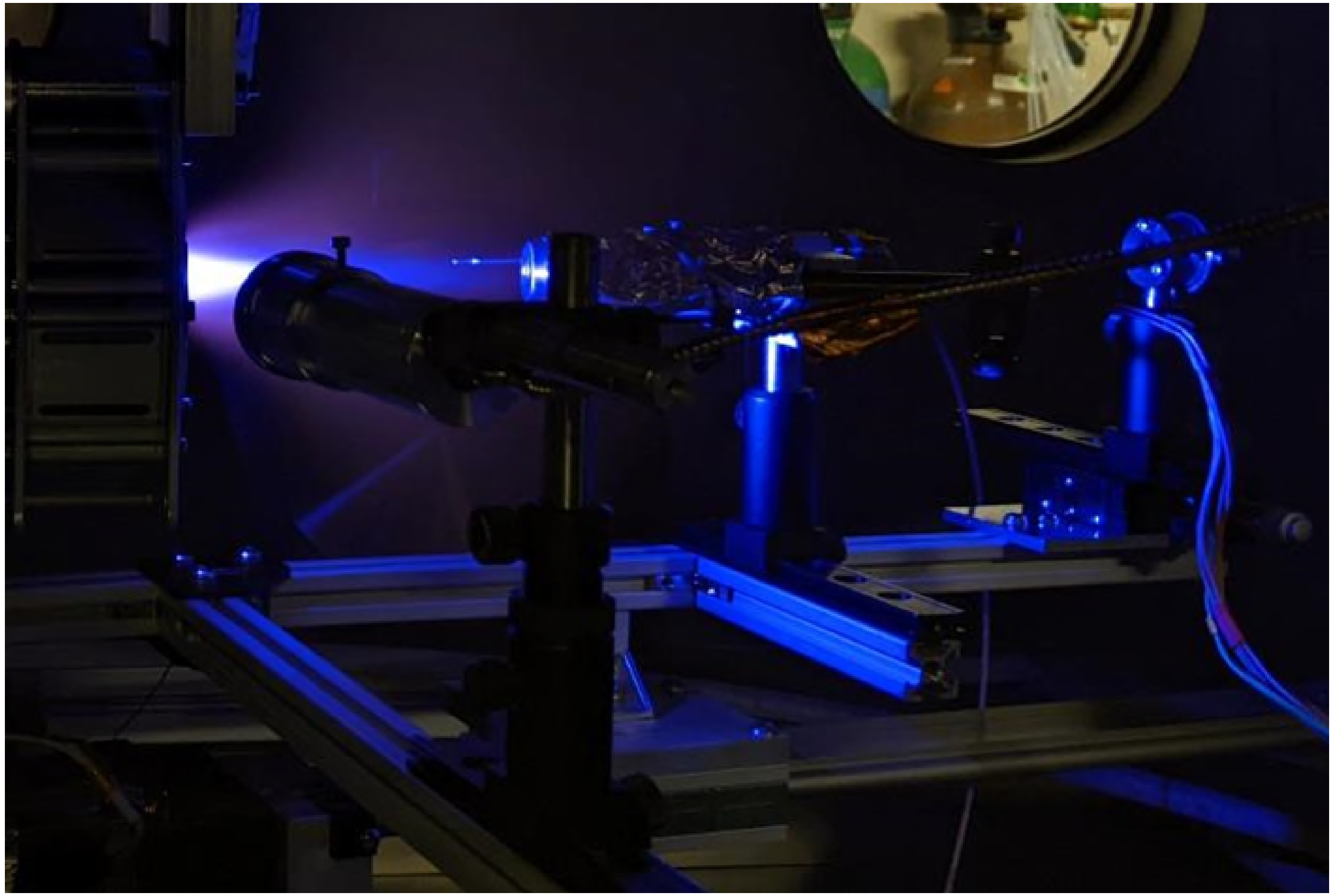


(b) LIF spectra of Xe I resolved along z

Summary of Performance Verification tasks

Retarding Potential Analyzer and Laser-induced fluorescence spectroscopy

Task 6 WP6000 - RPA vs. LIF measurements comparison



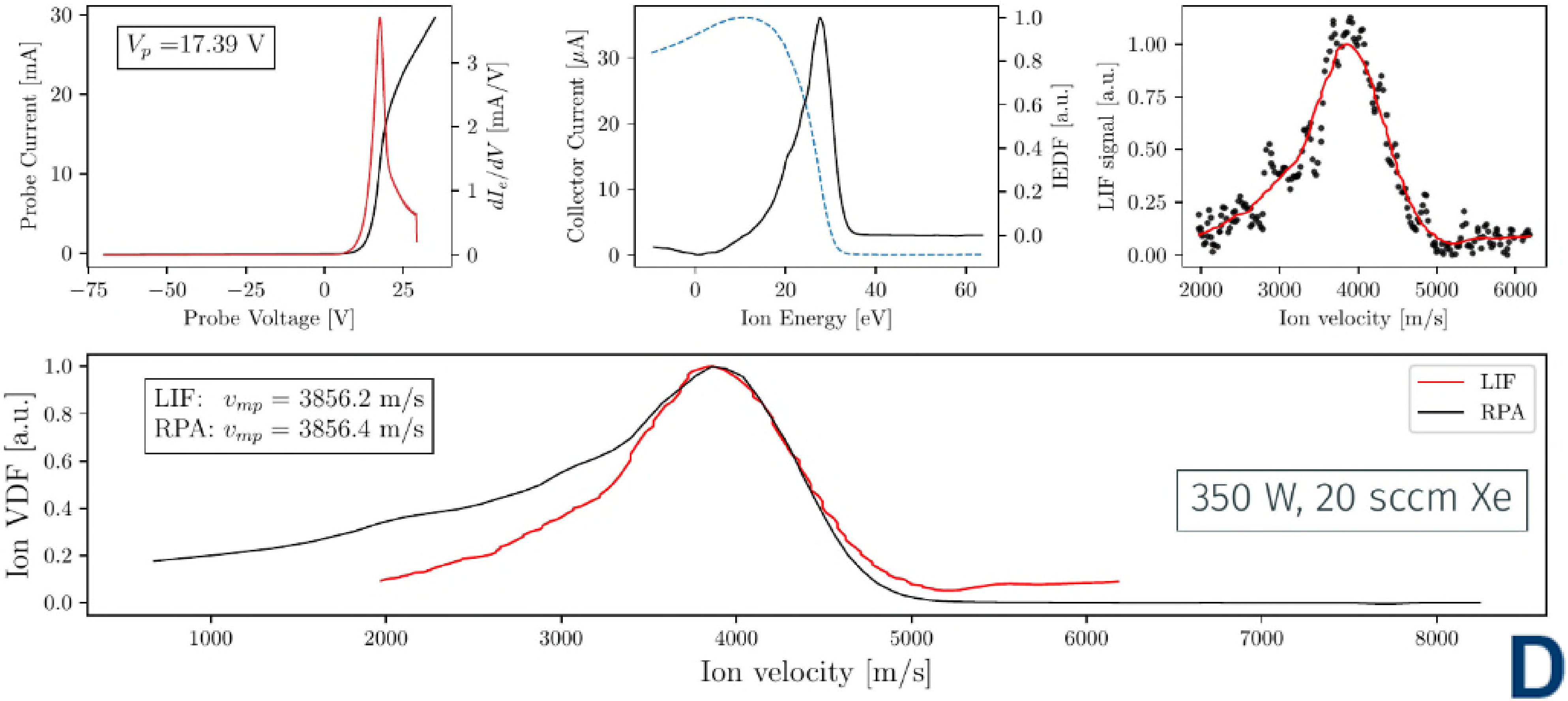
- Fixed axial position z = 12 cm
- Several power/mfr operating points
- Xe and Kr propellants

Summary of Performance Verification tasks

Retarding Potential Analyzer and Laser-induced fluorescence spectroscopy

Task 6 WP6000 - RPA vs. LIF results

- Example of RPA vs. LIF data point

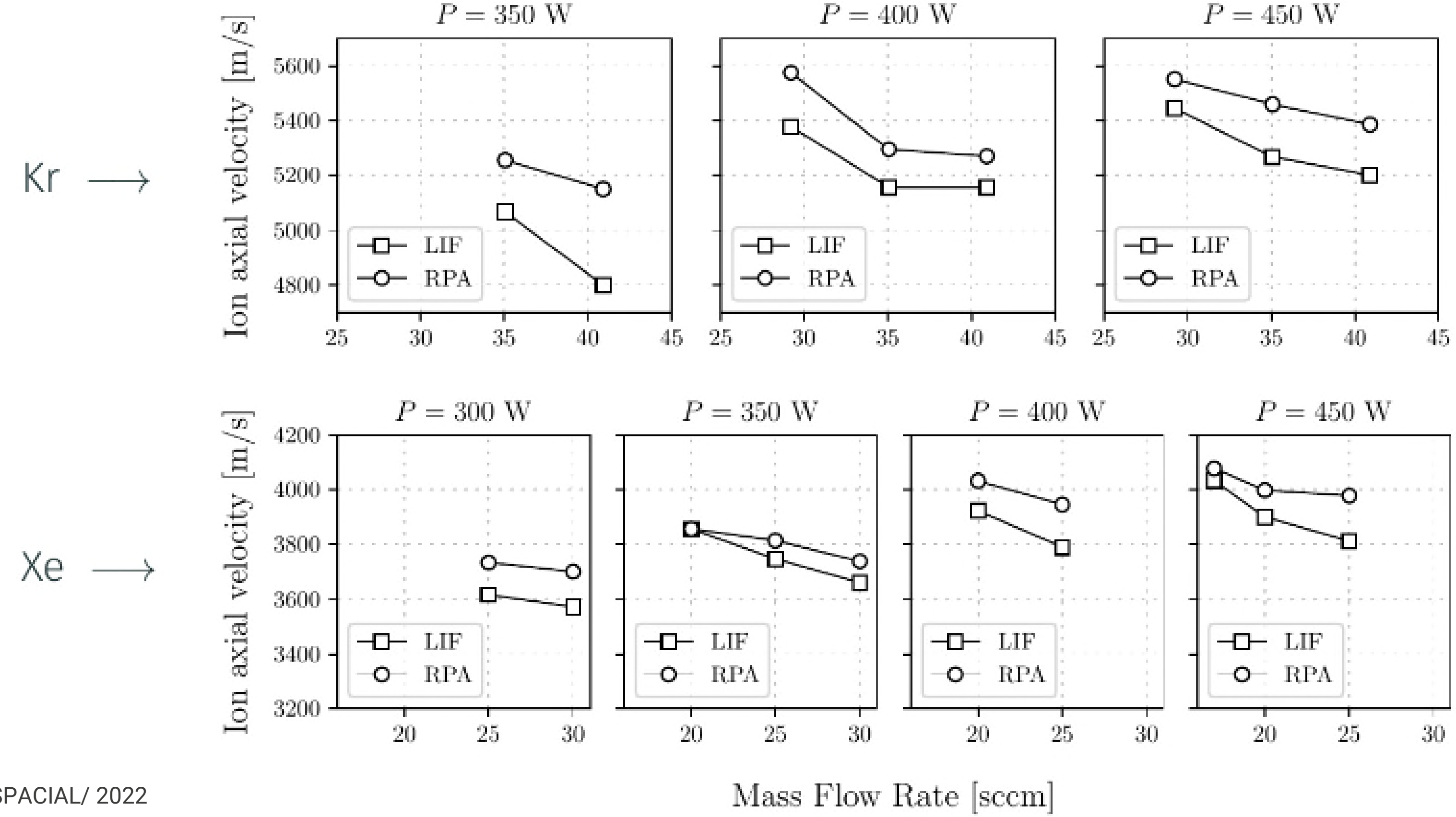


Summary of Performance Verification tasks

Retarding Potential Analyzer and Laser-induced fluorescence spectroscopy

Task 6 WP6000 - RPA vs. LIF results

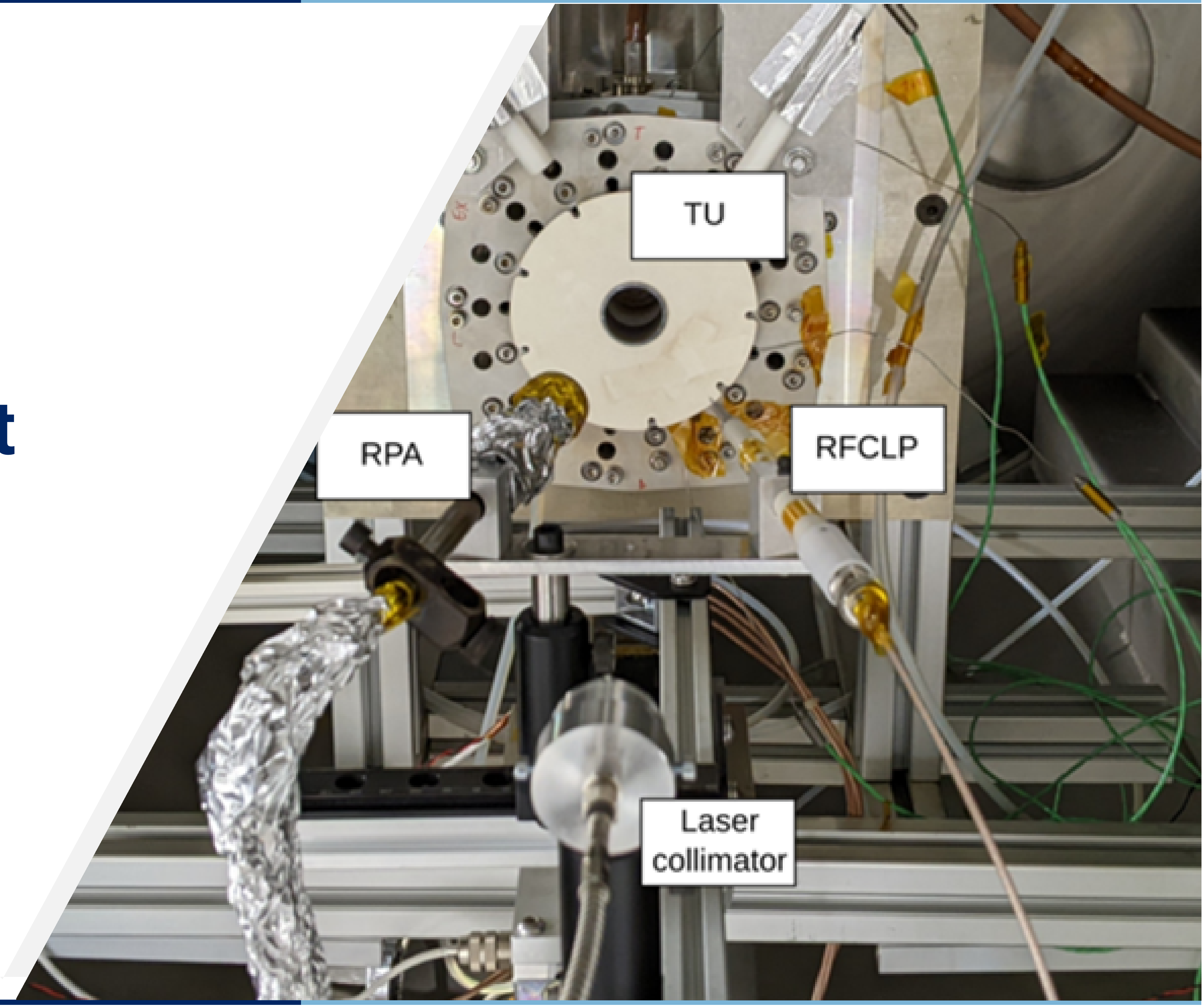
- Parametric RPA vs. LIF show good agreement
- Relative error close to LIF absolute resolution (~60 m/s)



$\mu_\varepsilon = 184$ m s^{-1}
$\sigma_\varepsilon = 71.9$ m s^{-1}

$\mu_\varepsilon = 96.3$ m s^{-1}
$\sigma_\varepsilon = 47.7$ m s^{-1}

Results assessment and open discussion



Results assessment and open discussion

RFCLP - Conclusions and recommended practices

- For dense enough plasmas (10^{16} m^{-3} or higher) the use of probes LP1 or LP2 yields to reasonable results with small perturbation when measuring at the near field. On the contrary, LP3 and LP4 could saturate in current (sourcemeter dependent).
- For low densities (10^{16} m^{-3} or below), the use of LP2 is not recommended (OML cylindrical is no longer valid).
- For all the explored range, thin sheath limit never applies.
- Gradients at the vicinity of HPT05M outlet are large, probe positioning and alignment are critical; LP3, LP4 perturb too much the whole discharge.
- Secondary electrode size seems to be irrelevant, 3cm^2 is enough.
- Tip contamination might introduce noise on the acquired curves.
- According to LP2 sequences, plasma conditions are repeatable.

	5 sccm Xe	10 sccm Xe	20 sccm Xe
z < 50 mm	$L = 6$ mm, $D \leq 0.381$ mm	$L \simeq 6$ mm, $D \leq 0.254$ mm	$L < 6$ mm $D \simeq 0.254$ mm
50 mm < z < 250 mm	$L \geq 6$ mm $D \simeq 0.381$ mm	$L \geq 6$ mm $D \simeq 0.381$mm	$L \geq 6$ mm $D \simeq 0.381$mm
250 mm < z < 400 mm	$L > 6$ mm $D \geq 0.381$mm	$L > 6$ mm $D \geq 0.381$mm	$L > 6$ mm $D \geq 0.381$mm

Results assessment and open discussion

FC results - Azimuthal scan example and main conclusions

- FC1 shows a good response in terms of current saturation at low mass flow rates (5 - 10 sccm).
- FC2 shows a better response with respect to FC1 at large mass flow rates (20 sccm) due to its vented body.
  - ***Neutral density*** inside the Faraday Cups is an important factor to be considered in the design process, particularly at large mass flow rates.
- The **collimator bias strongly modifies the ion optics**. It might reduce several times the collected current when it acts as an ion repelling electrode, and it focuses the beam (increasing current) at low biases.

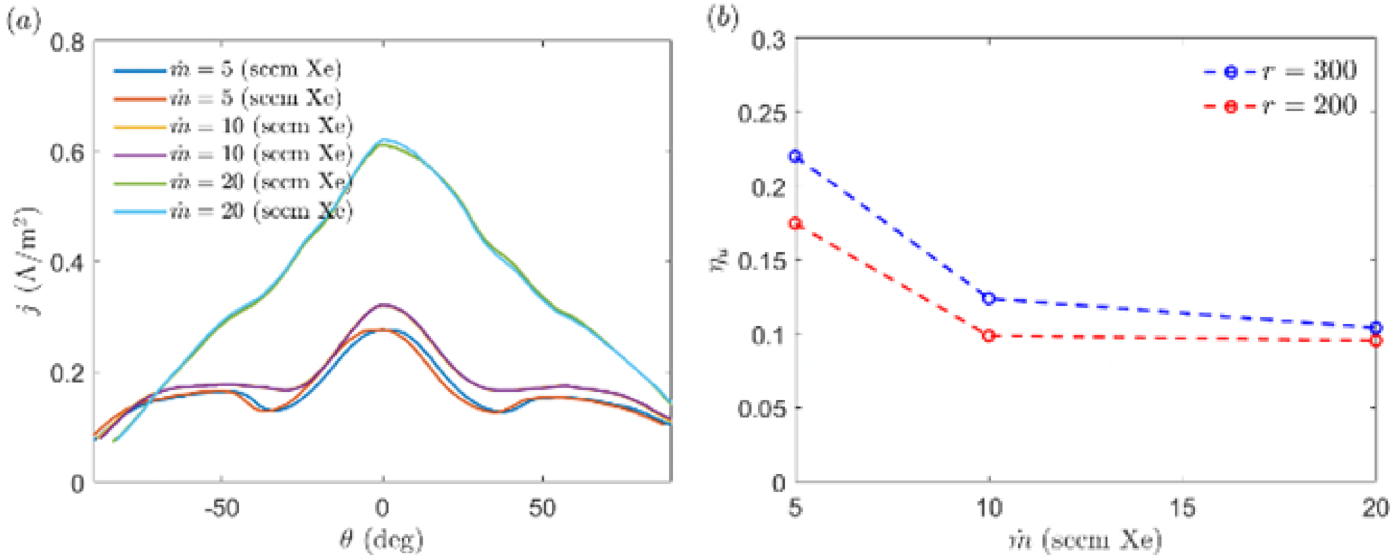
Future work

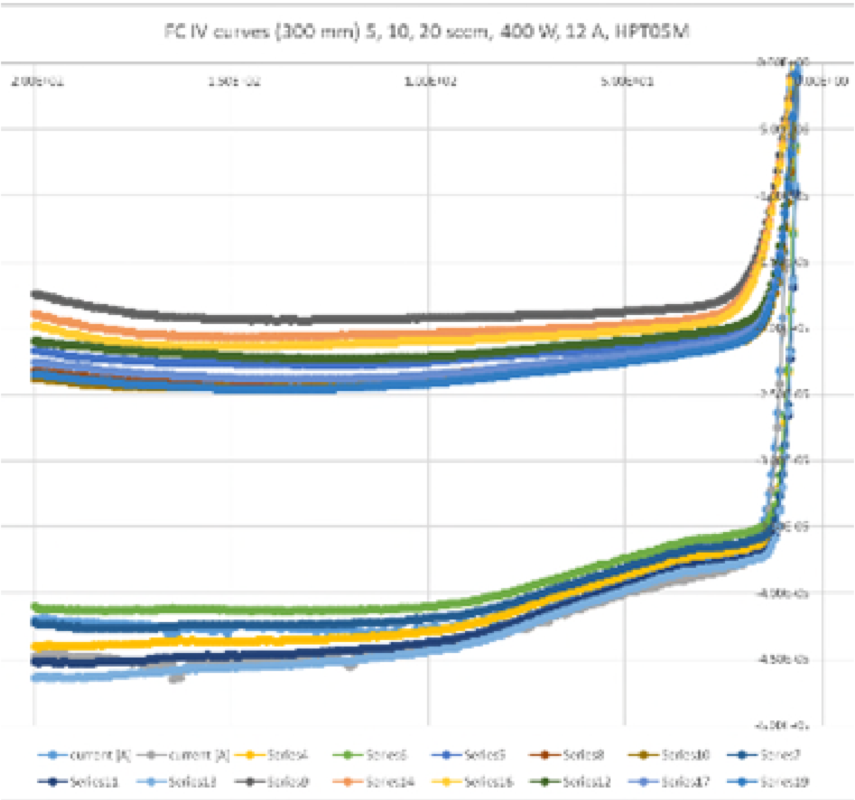
- Test different collector materials to assess the behaviour with respect to SEE (should be a minor role because the length of the probe).
- An electrostatic thruster could be used for probe calibration. However, plasma properties at the plume of an ion thruster are very different than in magnetic nozzle plumes, so this calibration might not extrapolate to electrodeless plasma thrusters.

Results assessment and open discussion

FC results - Extended work

- Cleaning procedure for FC2 (vented)
- Better saturation at all mass flow rates.
- Primary electrons current depression > -100 V.
- Integrated results and propellant utilization.





DTK
Diagnosis ToolKit for Plasma Thrusters

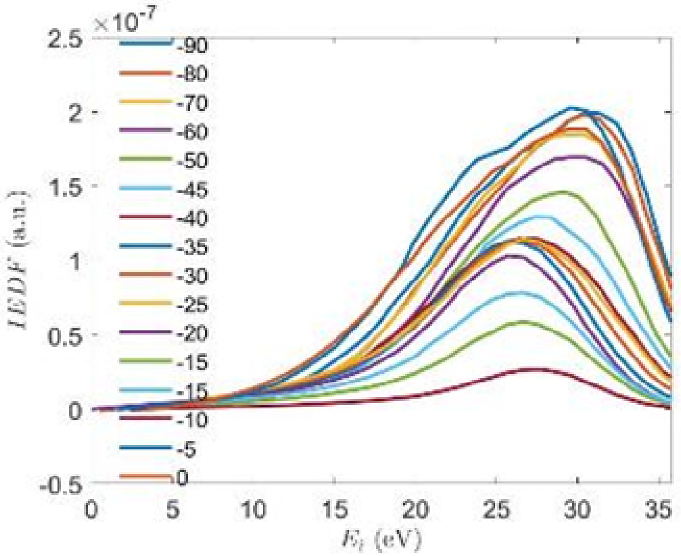
Results assessment and open discussion
RPA and LIF

- Parametric RPA vs. LIF measurements show good agreement (mean relative difference 2−3 %)
- Relative error close to LIF absolute resolution (~60 m/s)
- Pros and cons for each technique: sensitivity to charge state, magnetic field, local V_p; ion energy resolution; plasma perturbation; performance at low density; …
- Similar measurements using a GIT to optimize and better quantify the accuracy of RPA measurements (more defined ion beam energy and much larger range of ion velocity)

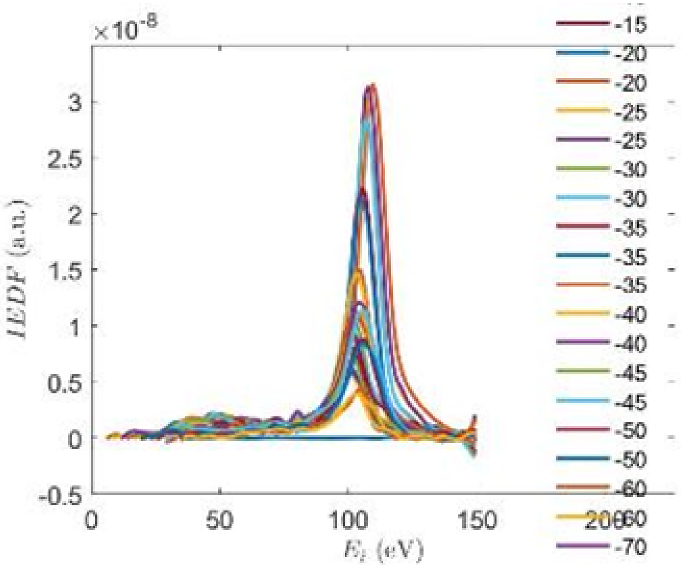
DTK as a whole

New data has been acquired with the RPA-UC3M, FC2, RFCLP

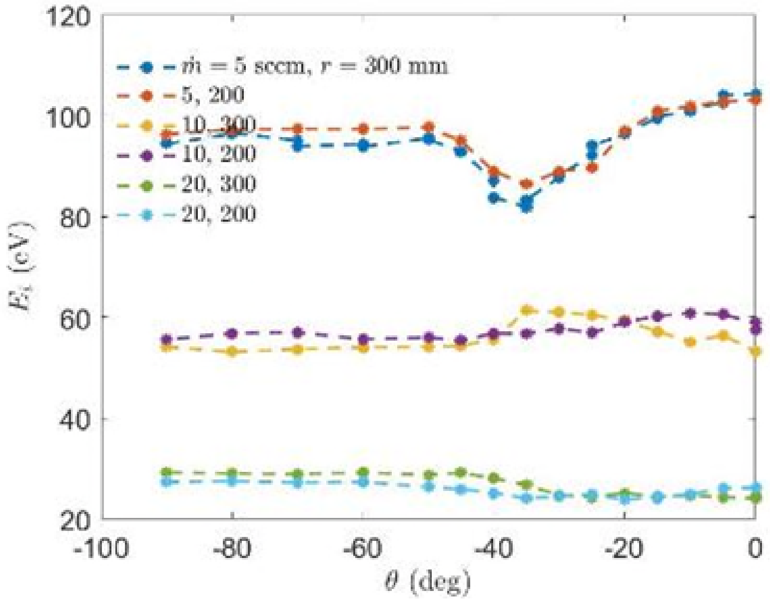
Mean Ion Energy (full half angle, 0deg, -90deg, r=200mm and r=300mm)



IEDF_HPT05M_400W_12A_20Xe_R200_results



IEDF_HPT05M_400W_12A_05Xe_R300_results

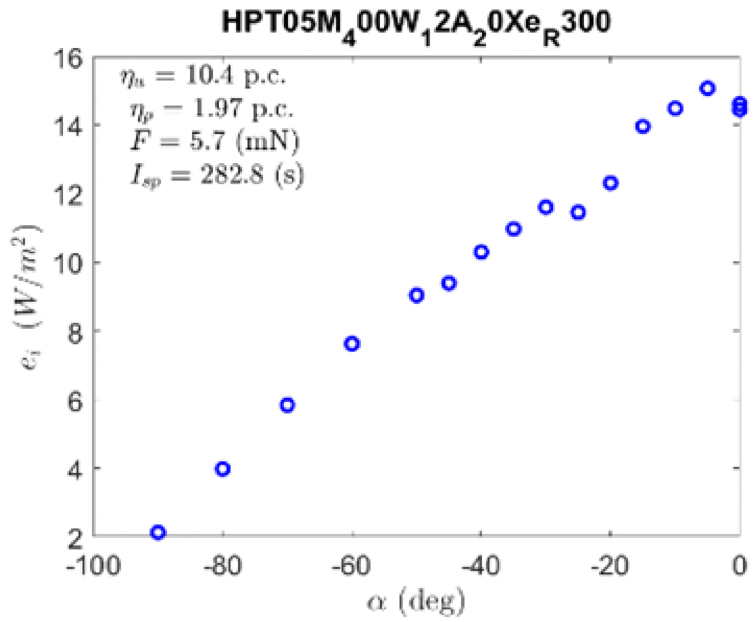


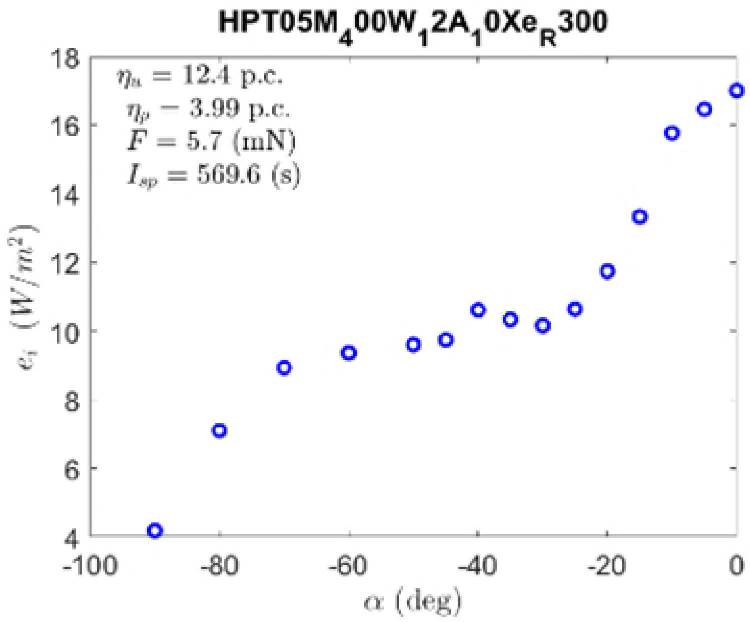
Diagnosis ToolKit for Plasma Thrusters

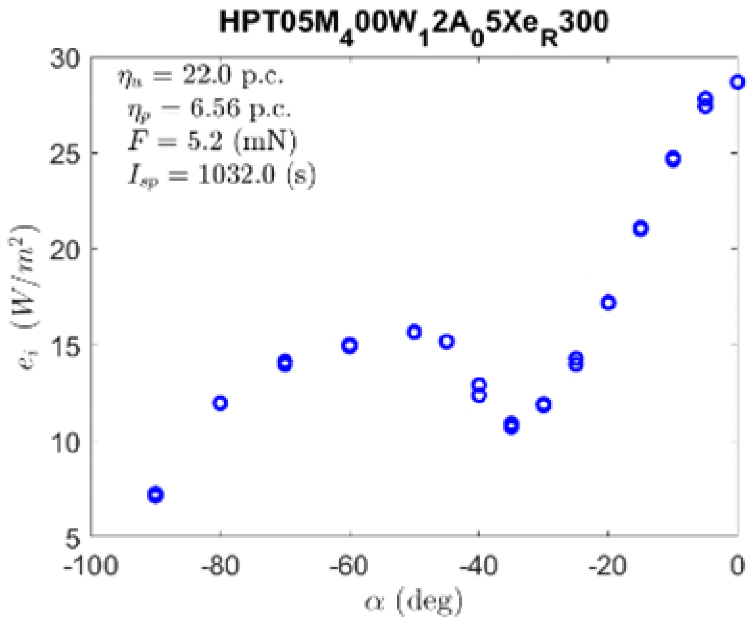
DTK as a whole

Current and energy combination → power conversion Pbeam/Prf

Power efficiency indirect estimation







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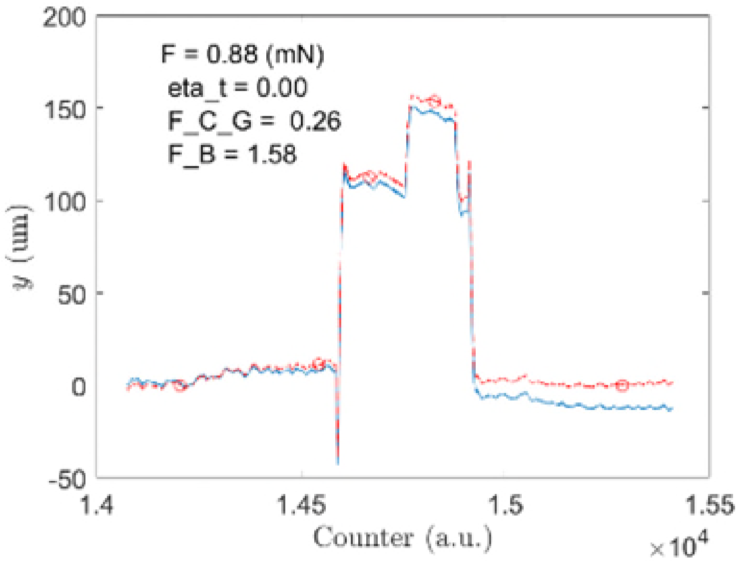
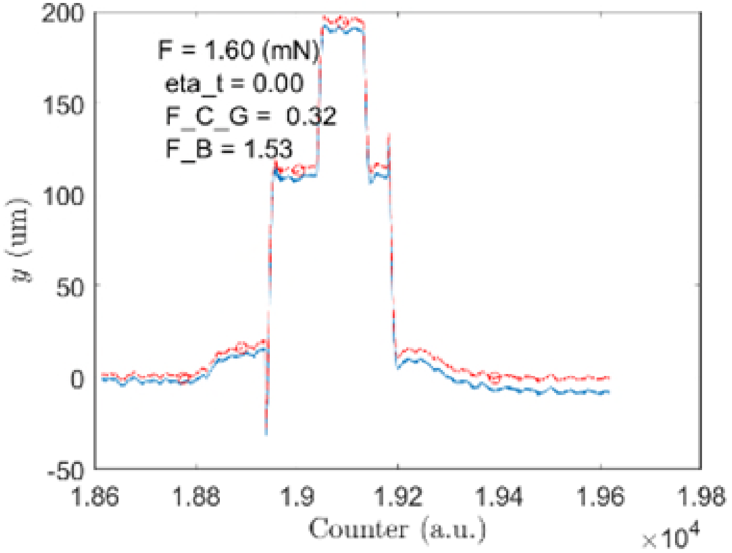
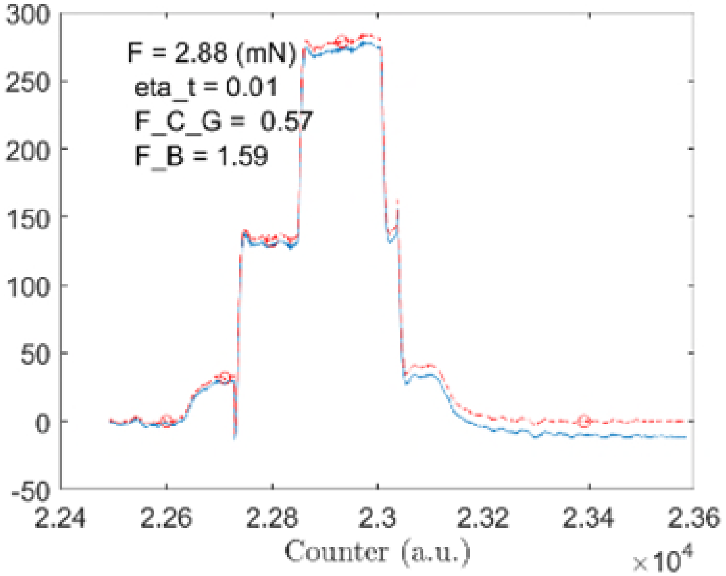
DTK as a whole
HPT05M TB - 400 W, 12 A







Probe overestimate the ion beam energy, overestimating as well thrust, specific impulse.
The small directivity of the FC (worse for FP) could explain the overestimation of the ion beam energy.

DTK

Diagnosis ToolKit for Plasma Thrusters

THANK YOU

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