Plasma analysis by optical diagnostics

CONSORZIO RFX
Ricerca Formazione Innovazione
CNR – ENEA - Università di Padova
INFN - Acciaierie Venete

Speaker: M. Ugoletti

Group: FO (optical diagnostics and analysis)

Phd students: L. Cinnirella, G. Emma, M. La Matina

Researchers: **L. Carraro**, M. Agostini, M. Barbisan, A. Belpane, F. D'Isa, P. Franz, L. Giudicotti, I. Mario, R. Milazzo, M. Ugoletti, B. Zaniol

The optical diagnostics group

- **WHO?** Group composed of 14 people: 3 PhD students, **11**researchers (**3** EUROFUSION funded)
- **WHAT?** Study of the properties of the plasma observing the electromagnetic emission with passive and active diagnostics.
- **WHERE?** Padua and not only!
  - → Fusion plasmas: **RFX-MOD2** and most of the world tokamaks (TCV @Switzerland, ASDEX @Germany, JET @UK, JT60SA @Japan, including the **D**ivertor **T**okamak **T**est project @Rome)
  - → Neutral beam: **SPIDER-MITICA–minion** and other laboratories (IPP @Germany, QST and NIFS @Japan)
- **HOW?** Experimental set up of instrumentations, data analysis, impurity transport modelling and simulations, tomographic reconstructions

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Passive diagnostics: Plasma spectroscopy

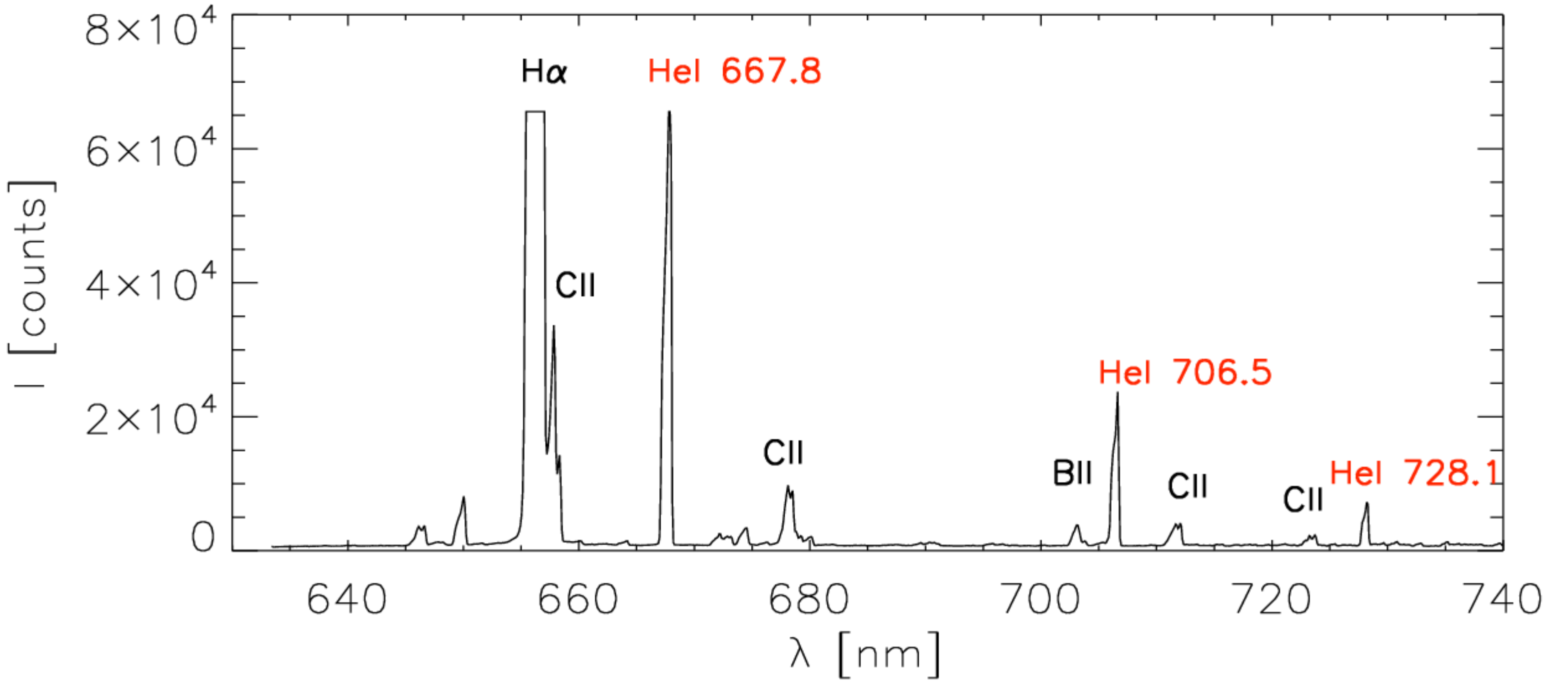
Spectroscopy measures the electromagnetic radiation of the plasma

➡ Main gas ➡ Impurity coming from the wall ➡ Impurity injected for diagnostics purposes

- Very powerful and not perturbing diagnostic tool, especially for hot and high density plasmas where no material probe can be inserted.

- Spectroscopy tries to understand what emission registered at a specific energy/wavelength can tell us about the emitter plasma properties (density, temperature, motion, **E** and **B** fields...)

Passive diagnostics: Plasma spectroscopy



- Who is emitting?
- With which energy?
- Where?

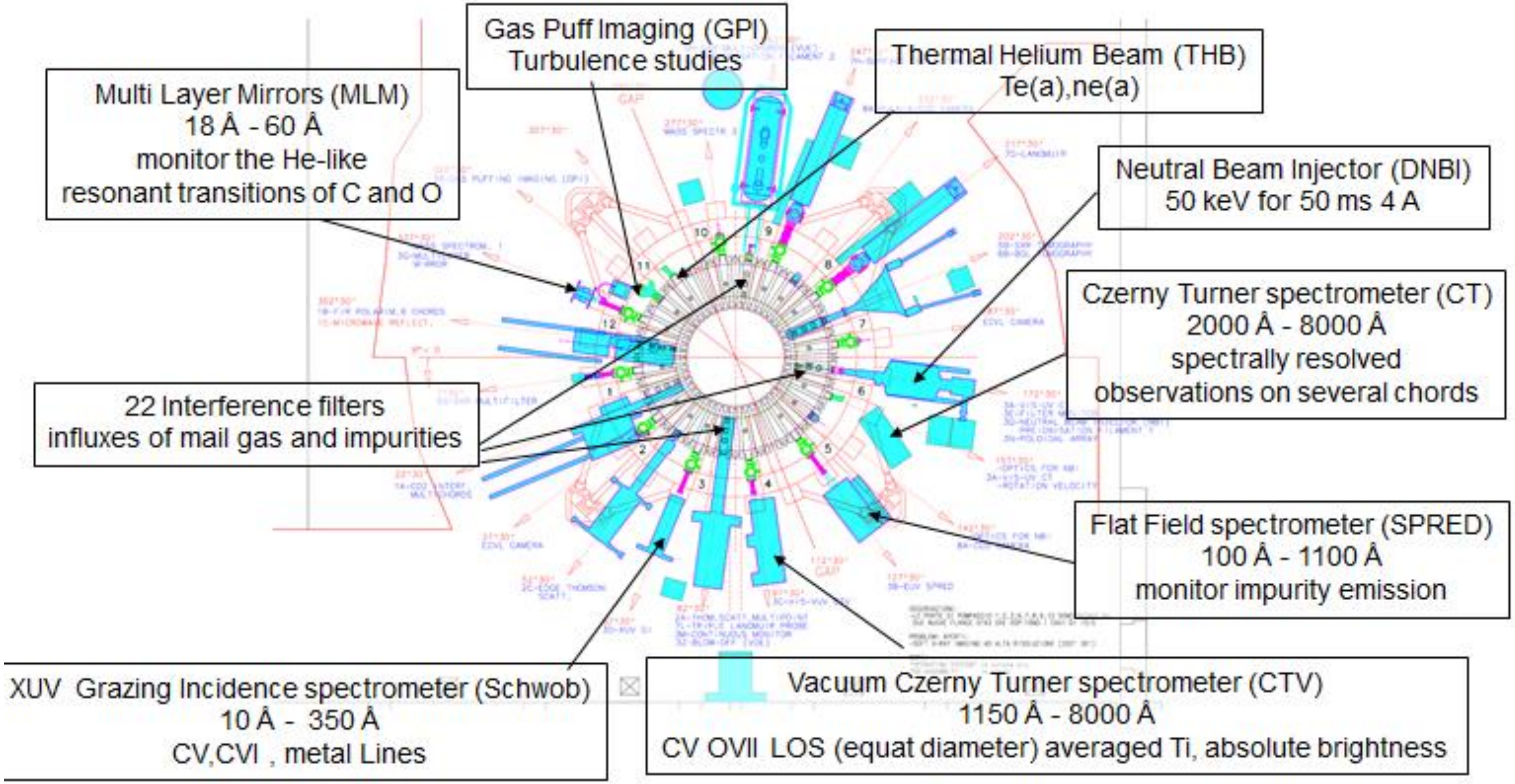
Each element can be recognized from its ***line emission spectrum***: the absolute intensity of a transition (line emission) is directly correlated with the population density in the excited state, the upper level.

Atomic models are required to predict the population of each individual level of an ion/atom/molecule

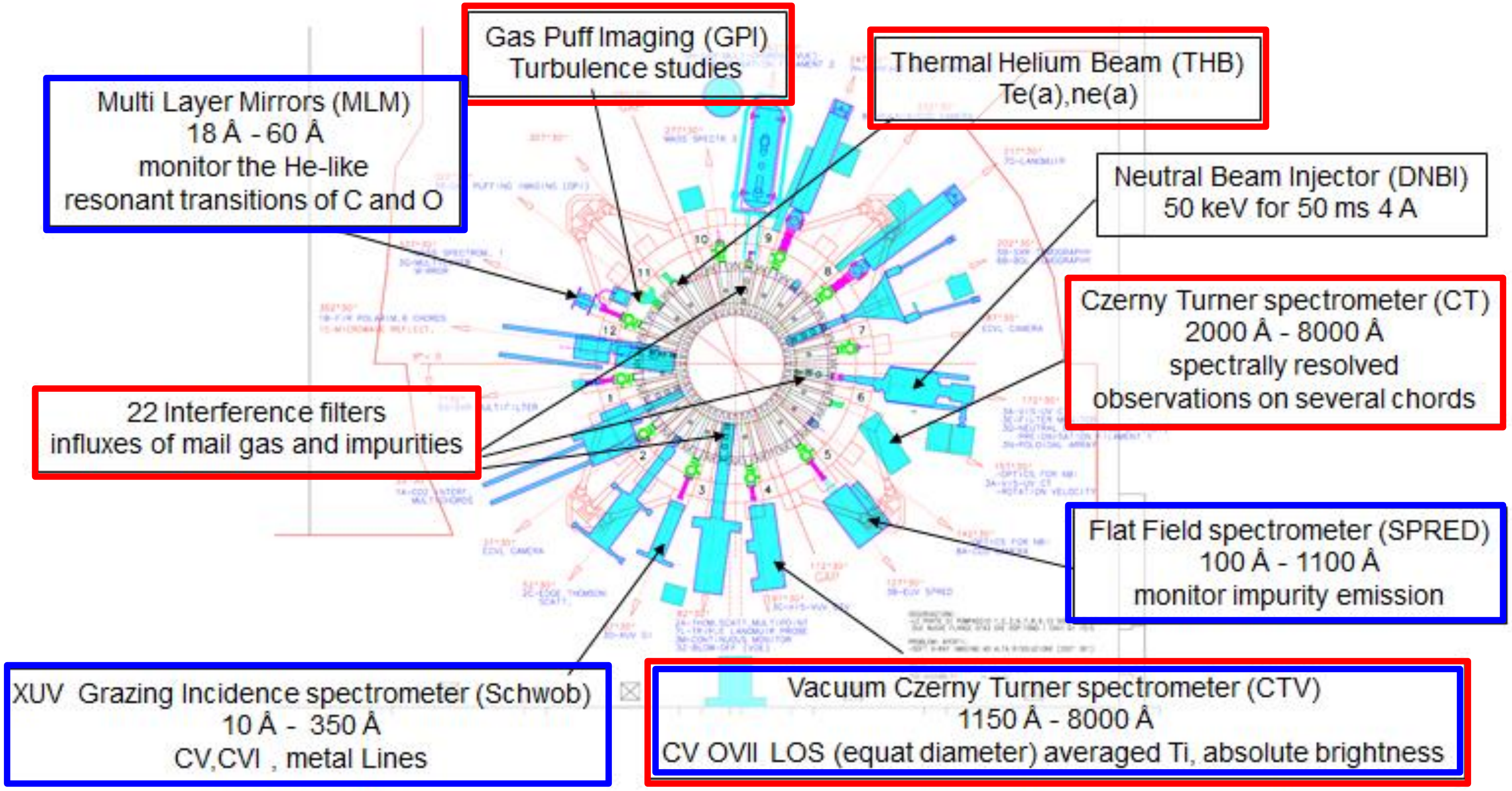
What we measure?

- **Plasma composition** looking at the raw spectra
- **Ion velocity** by measuring the line emission Doppler shift
- **Ion temperature** by measuring the line emission Doppler broadening
- **Electron temperature** from selected line emission (in the visible range for the edge, and in the X-ray for the core)
- RFX-mod **Plasma wall interaction** quantified with 2D images and measurement of the particle flux from the wall
    - 2D spatial profiles are obtained

Layout of spectroscopic diagnostic in RFX-mod



Layout of spectroscopic diagnostic in RFX-mod



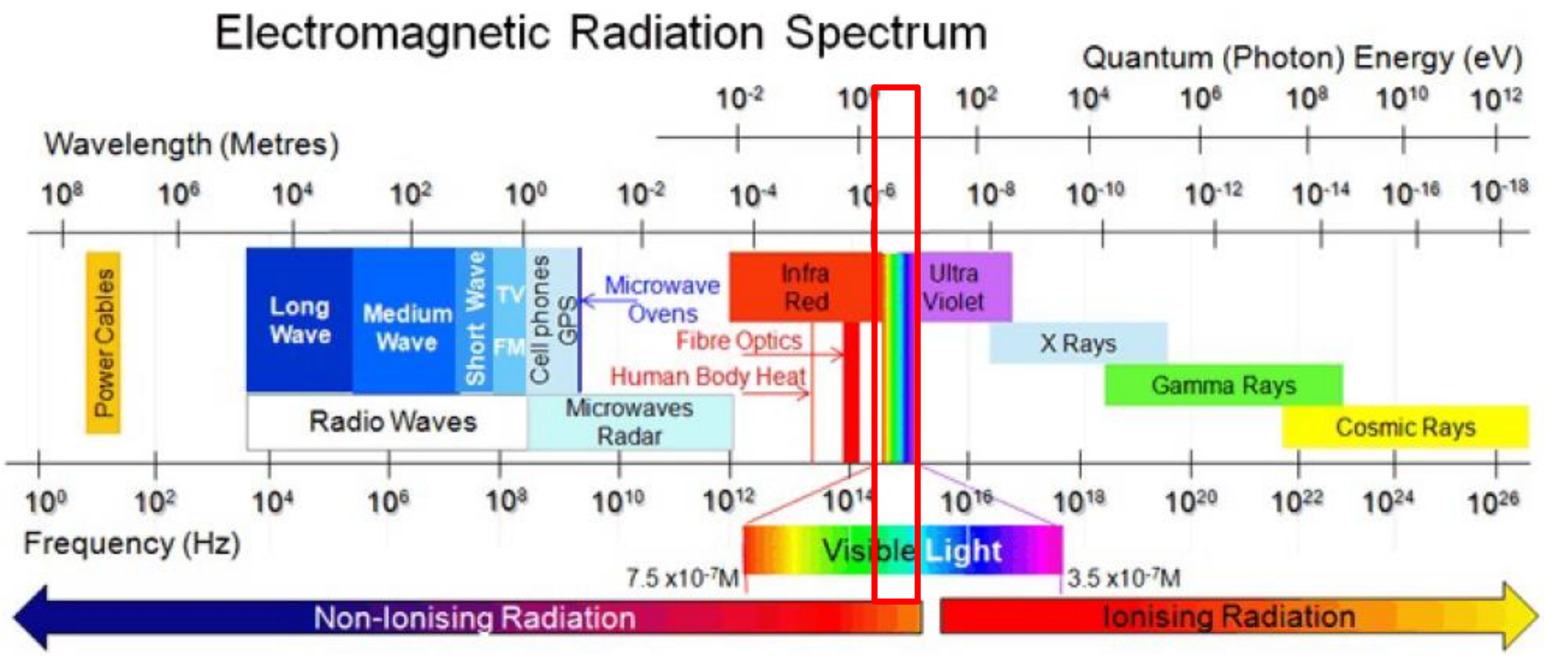
Visible light

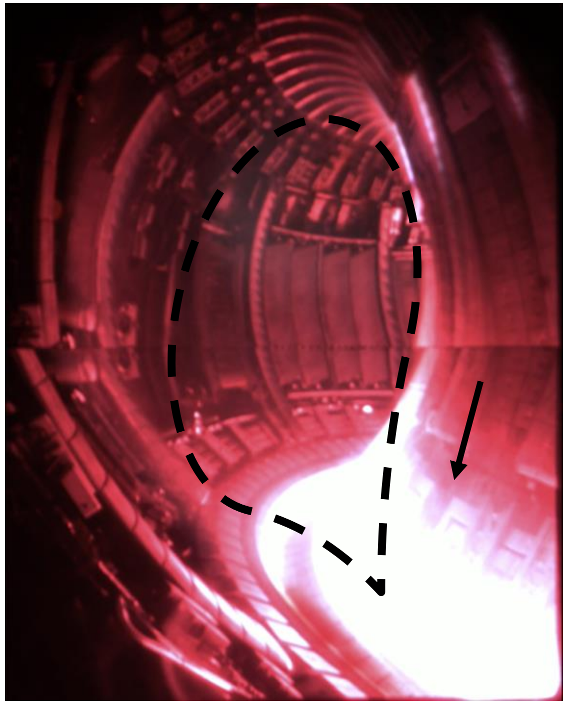
UV – x-rays

+ NEW DIAGNOSTICS thanks to **PNRR funding**:

- MANTIS polychromator
- Light Impurity Tomography

Spectroscopic measurements: visible light





https://euro-fusion.org/eurofusion-news/dte3record/

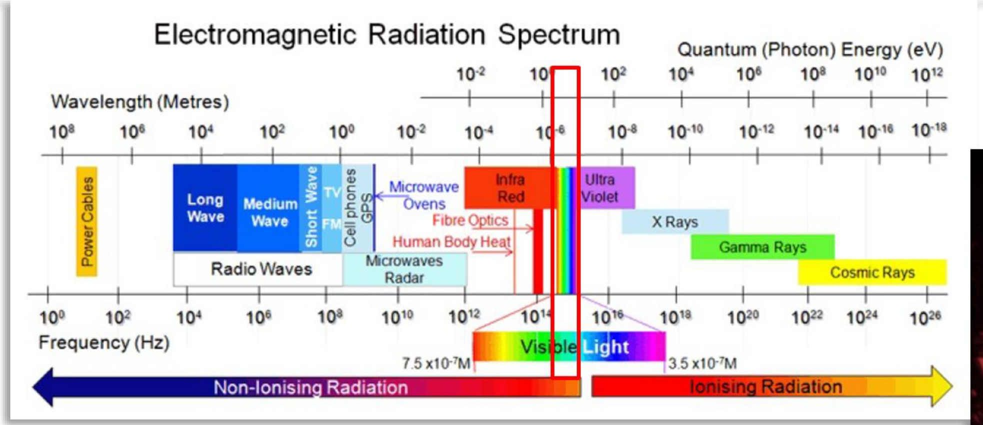
Photon energy: few eV

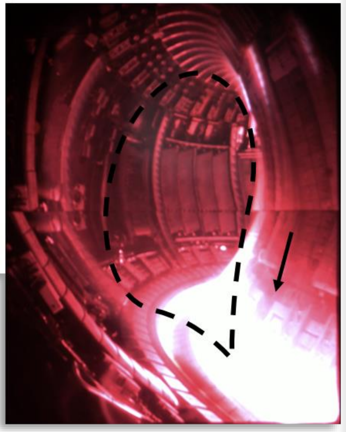
Spectral range: 350-800 nm – **Visible light**

Emitters: Molecules + atoms +low ionized particles

Detector: in air (technically easier), transmission optics in glass/interference filters

Spectroscopic measurements: visible light





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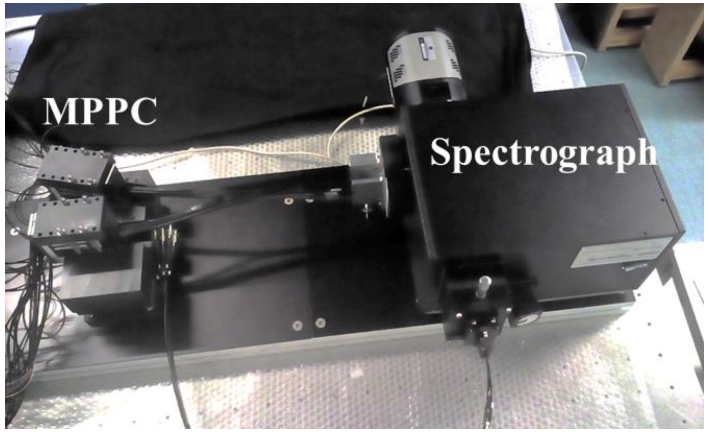
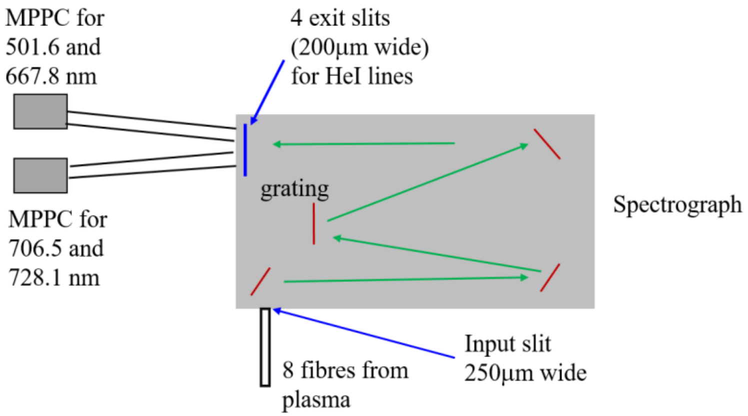
(Not perturbing) Thermal Helium Beam injected



Radial profile of electron temperature and density of the colder plasma edge

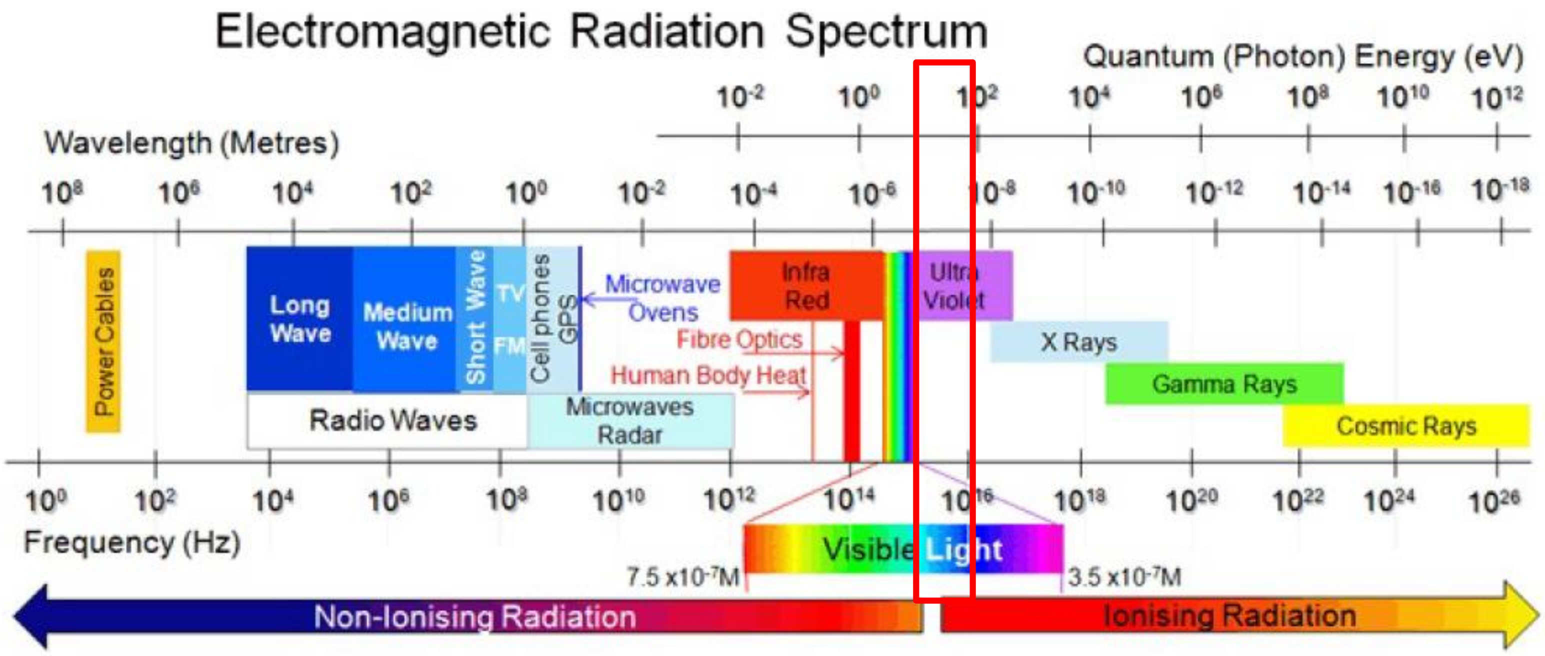
Non stationary plasma phenomena

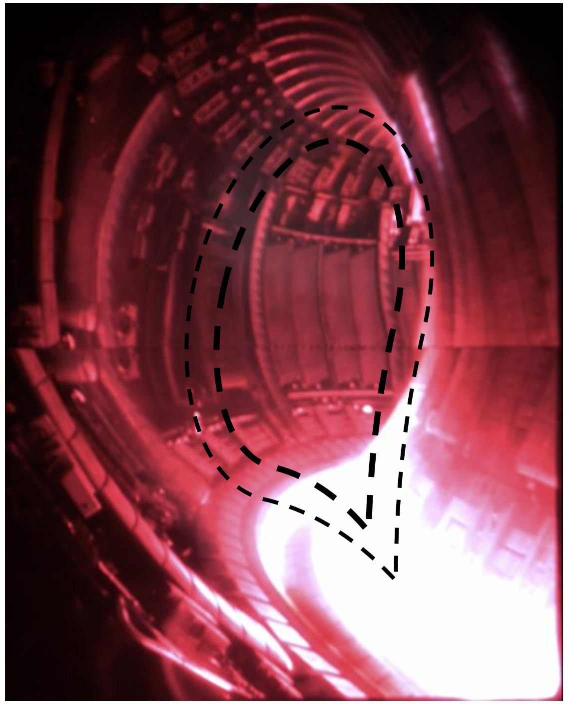
Turbulence



M.Agostini et al.,Rev. Sci. Instrum. ***91****, 113503 (2020)*

Spectroscopic measurements: UV





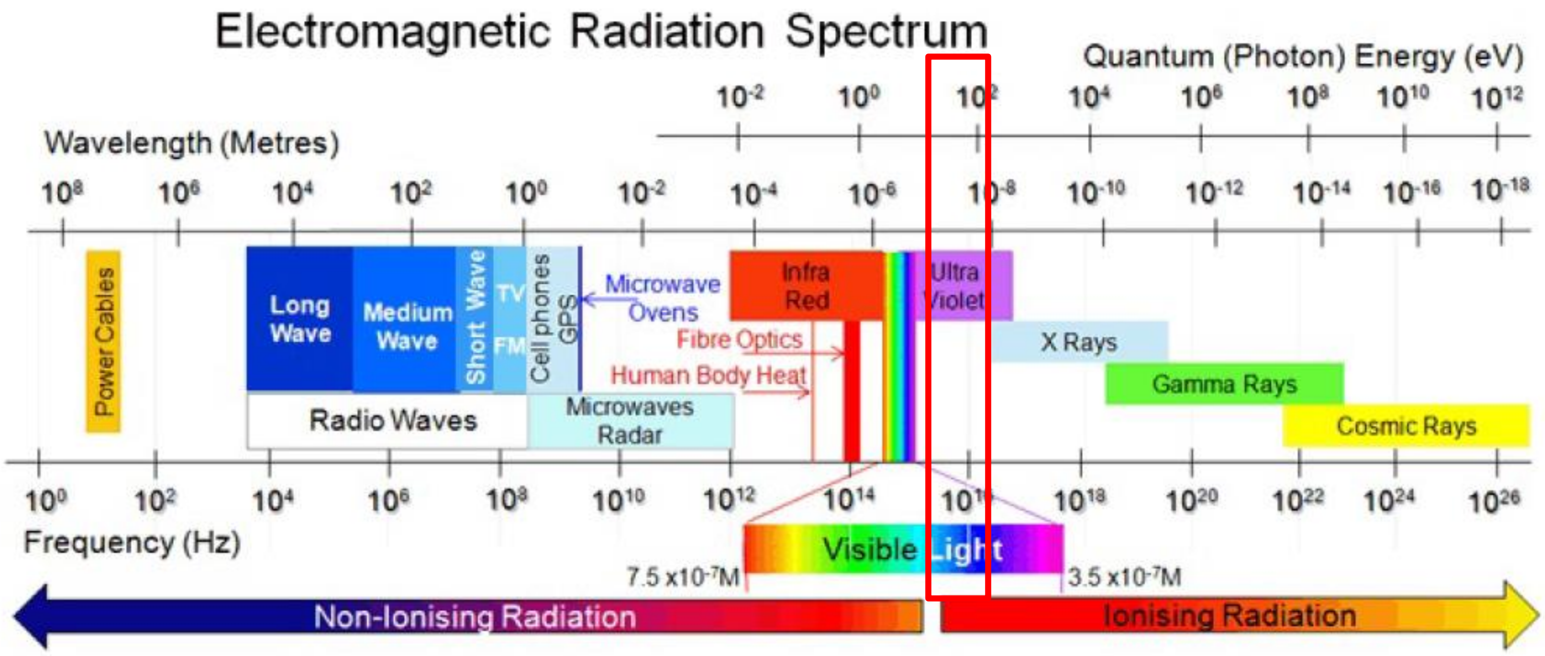
Photon energy: tenths of eV

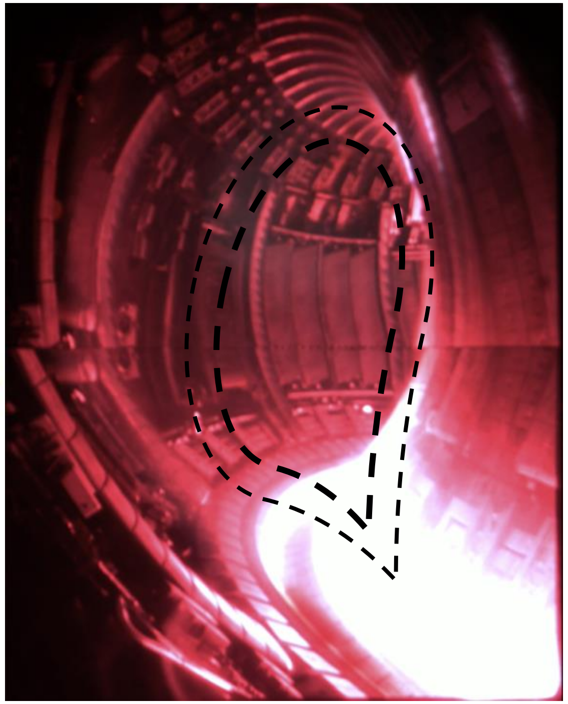
Spectral range: 180 - 400 nm – UV

Emitters: Neutral atoms + ions

Detector: in air (technically easier) transmission optics in quartz

Spectroscopic measurements: vacuum UV





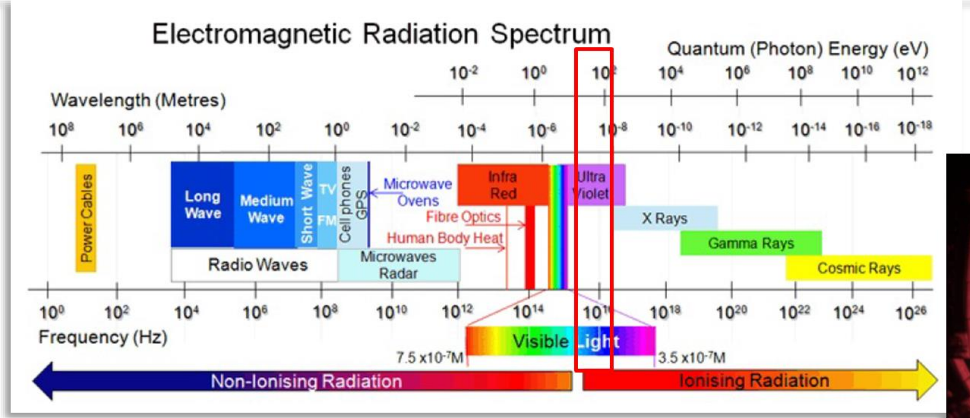
Photon energy: up to 100 eV

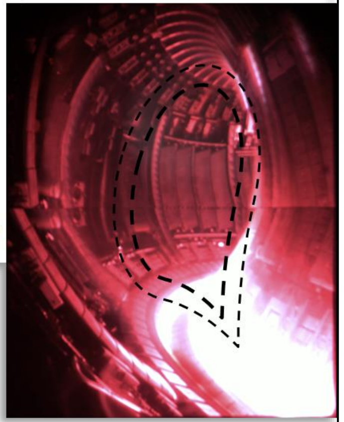
Spectral range: 3-180 nm – **vacuum UV**

Emitters: most of the radiated lines are here (hot plasma)

Detector: in vacuum (10^{-6} 10^{-7} $torr$) grazing incidence. Technically more difficult (low efficiency, strong optical aberrations)

Spectroscopic measurements: vacuum UV





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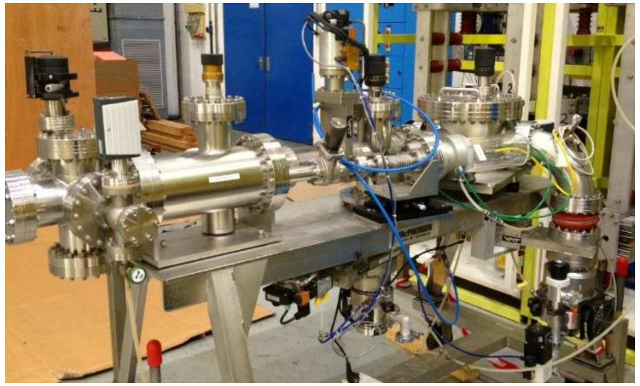
SPRED spectrometer (2105 g/mm)

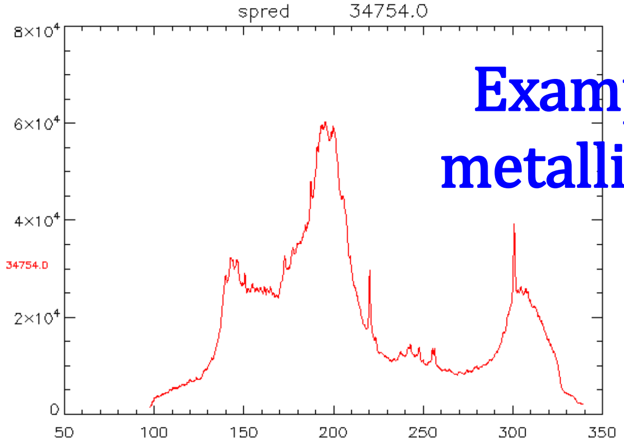


10-110 nm

$T_{e.max}$ $500 - 800\ eV$

$n_{e.max}$ $3 - 4\ 10^{19} m^{-3}$

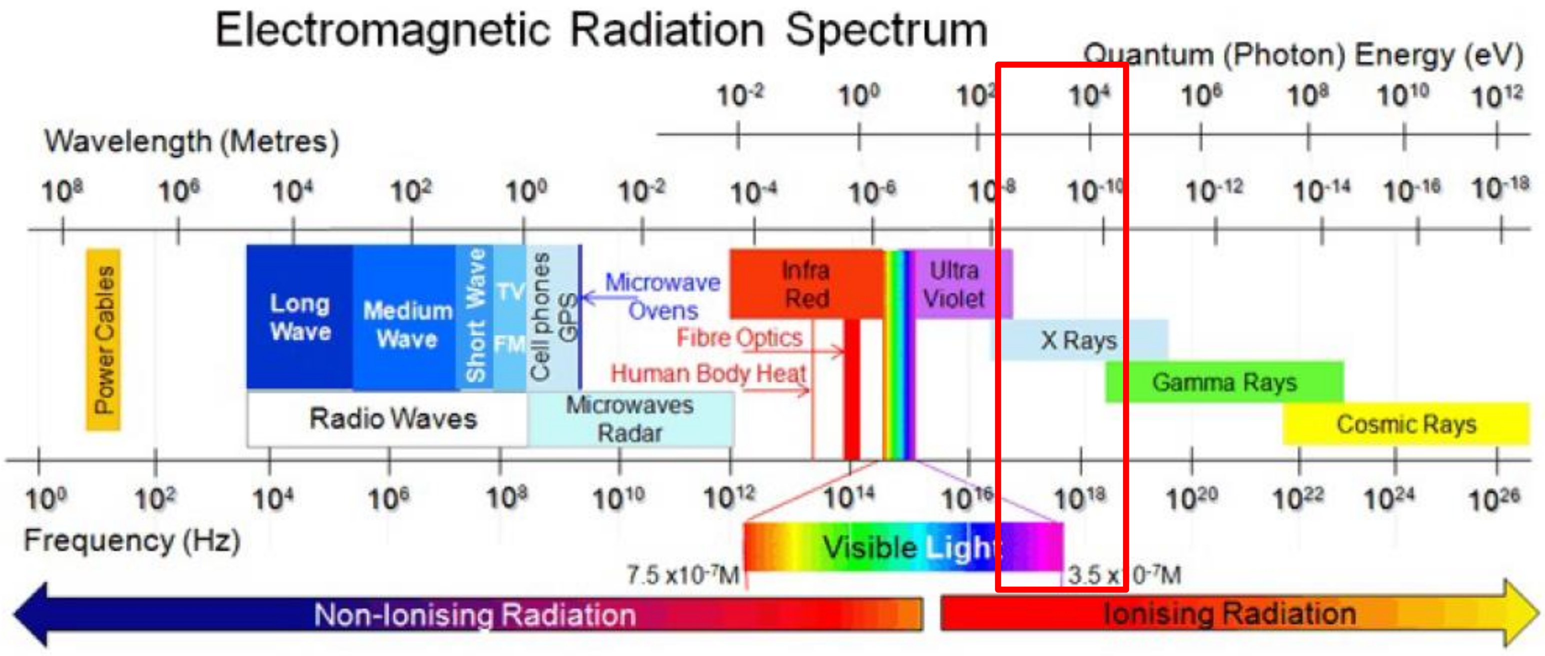
Monitoring impurity species emitting in the plasma

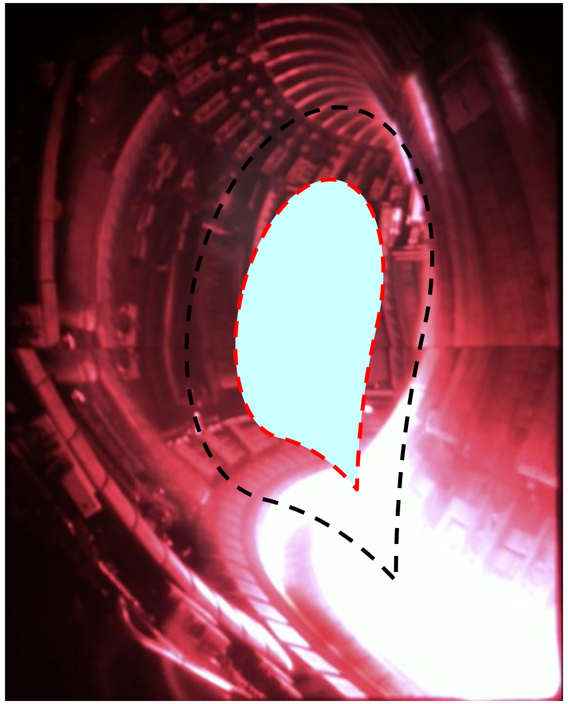


Example of metallic band

L. Carraro et al., Nucl. Fusion ***36****, 1623 (1996)*

Spectroscopic measurements: X rays





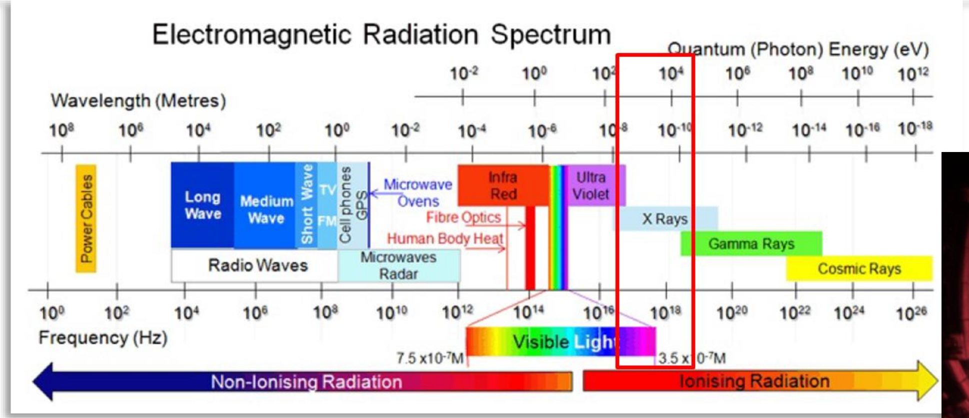
Photon energy: **>1 keV**

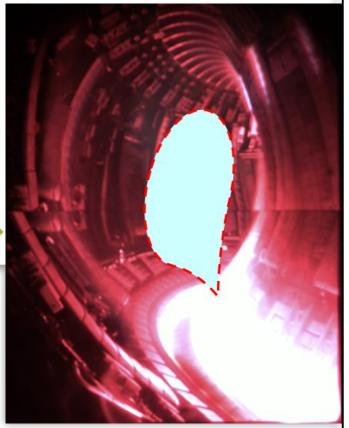
Spectral range: < 1 nm – **x-rays**

Emitters: most of the plasma radiation is here (core plasma)

Detector: in vacuum (10^{-6} 10^{-7} $torr$) crystal spectrometer.

Spectroscopic measurements: X rays





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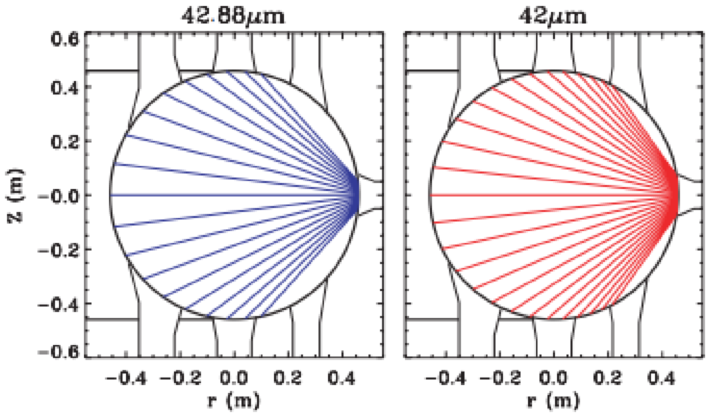
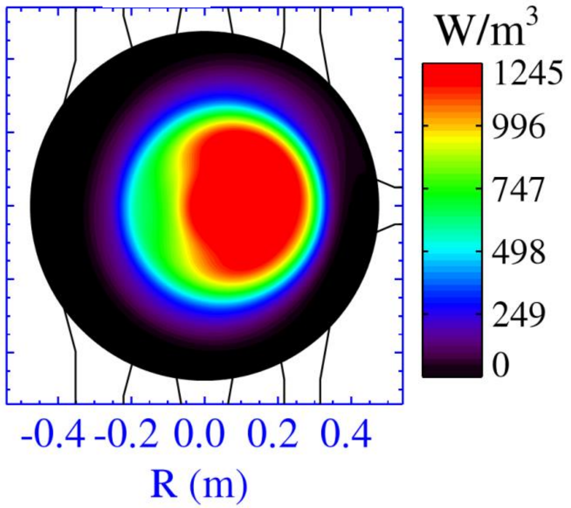
X rays tomography



SXR emissivity



- **103 lines of sight**
- **up to 100 kHz**
- **Beryllium foils of different thickness** allow the selection of certain range of energies to calculate the **Te profiles**.

P. Franz et al., Nucl. Fusion ***53****, 053011 (2013)*

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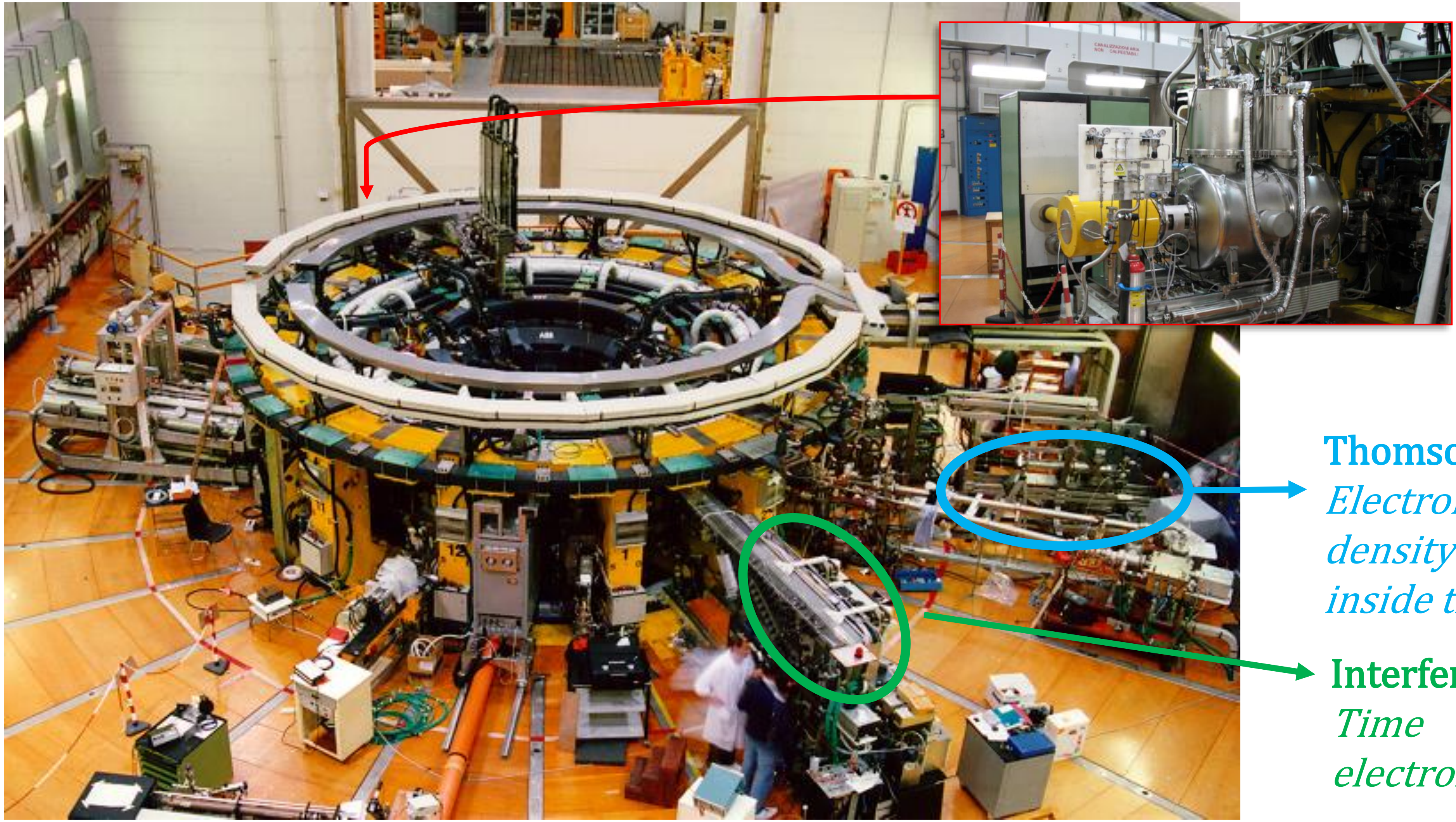
Active diagnostics



Diagnostic neutral beam

Measure of plasma impurities, ion temperature and flow, B field

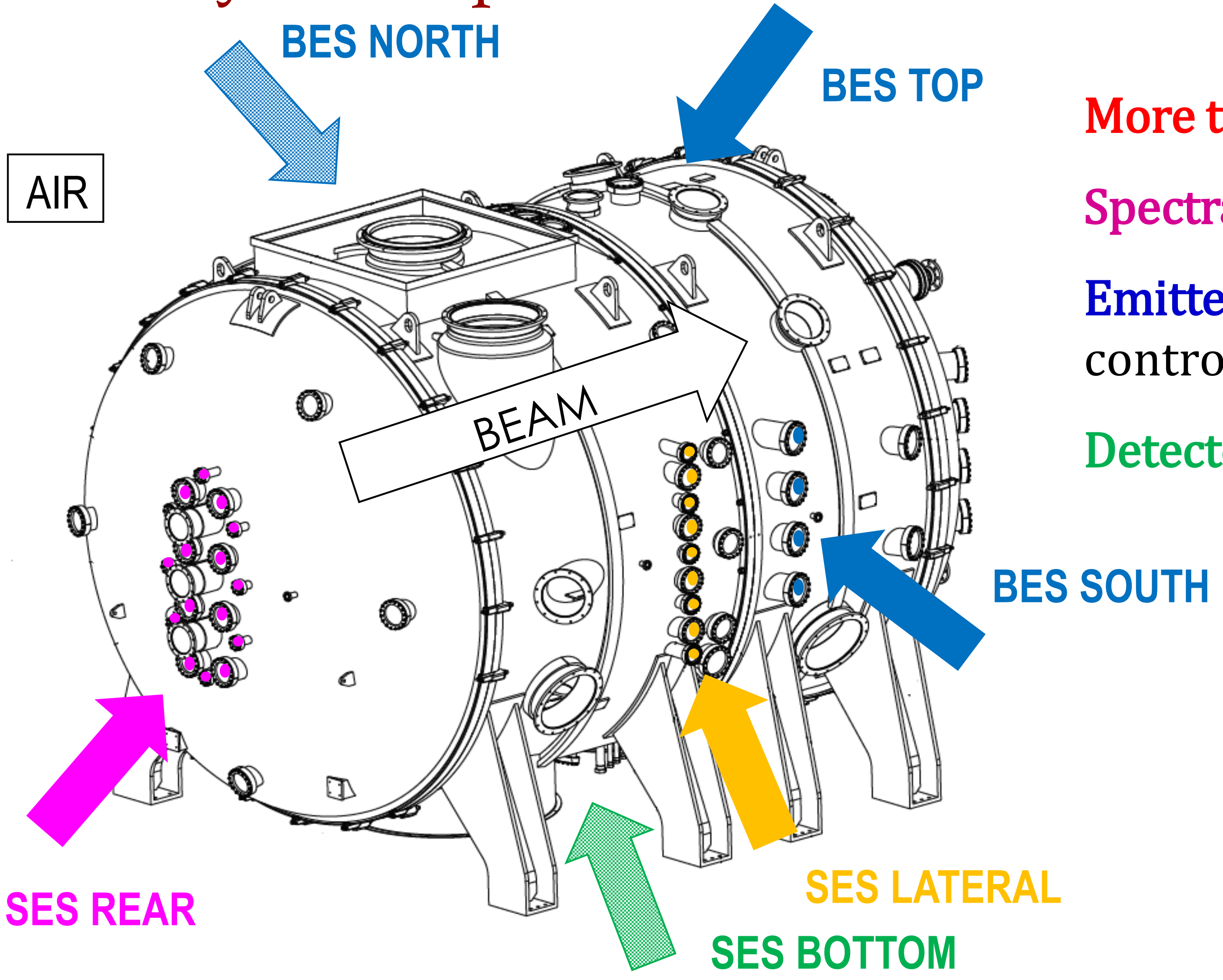
Thomson scattering:

Electron temperature and density at many locations inside the plasma

Interferometer:

Time evolution of electron density

Not only fusion plasmas: Neutral beam injector applications



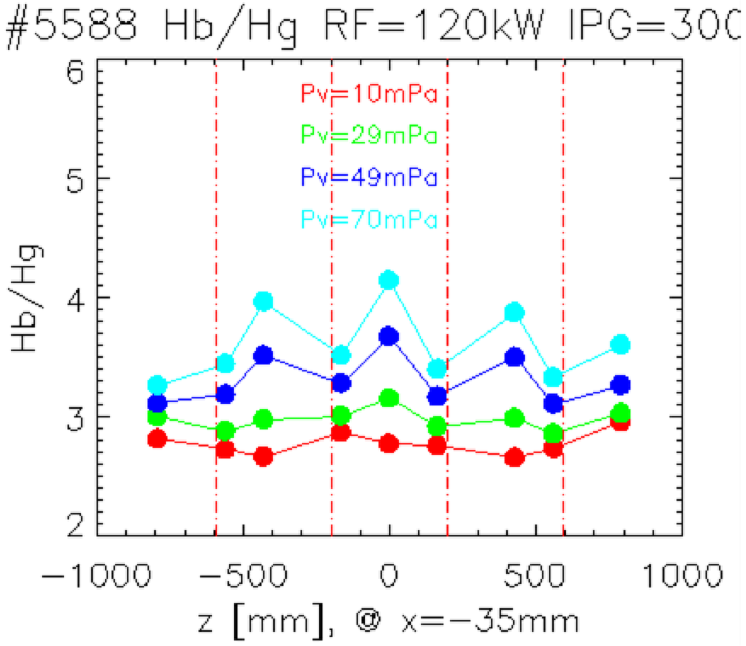
Source **E**mission **S**pectroscopy
Beam **E**mission **S**pectroscopy

More than 160 lines-of-sight

Spectral range: visible range (cold plasma)

Emitters: H and D molecules, neutral and ions; control of plasma impurities

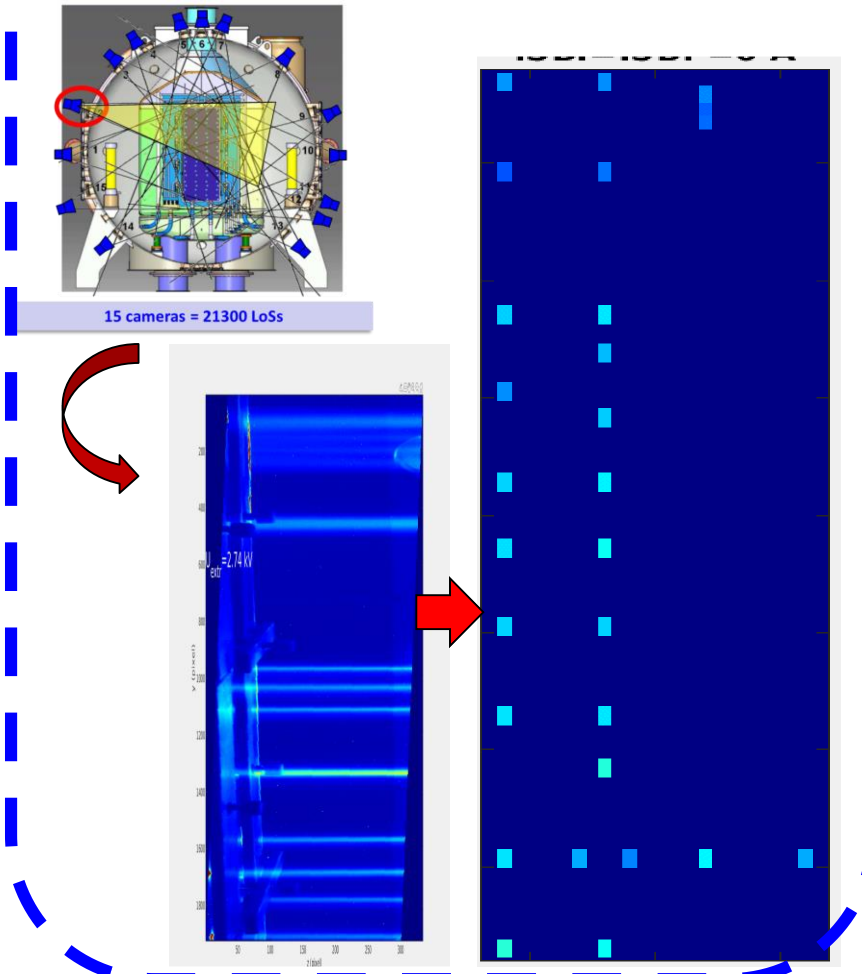
Detector: in air



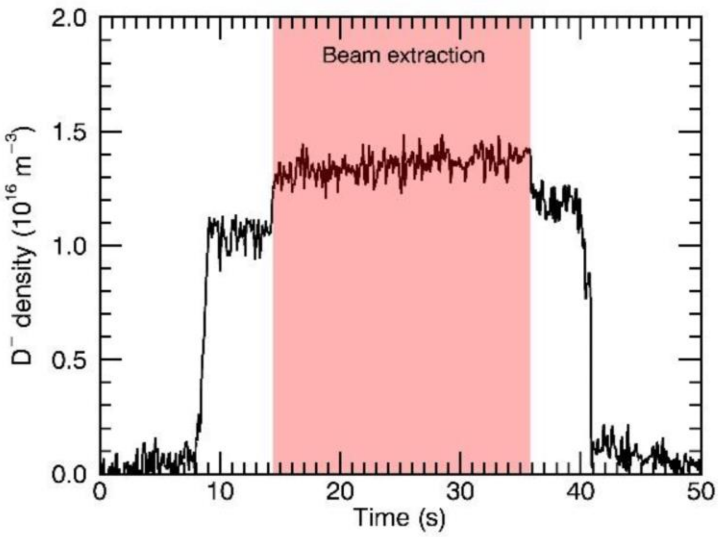
Example of vertical profile of the plasma emission

Not only fusion plasmas: Study of the beam emission

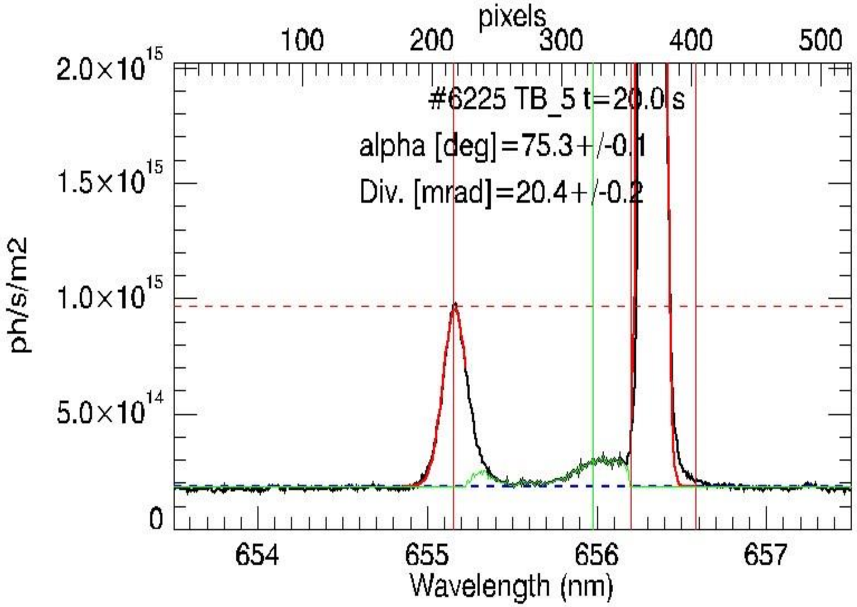
- Beam tomography with visible cameras



- Estimation of negative ion density D^-



- Estimation of beam divergence (Doppler shift)



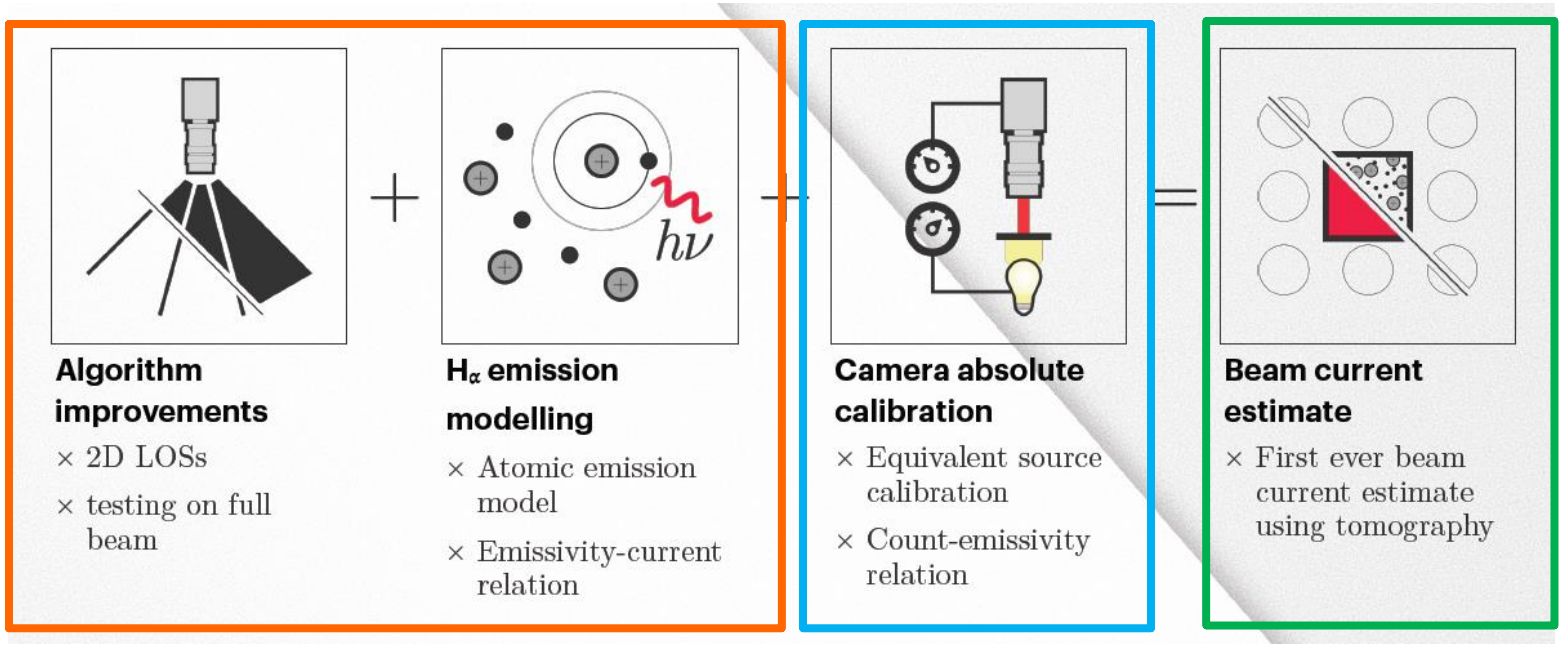
Example of Master Degree's Thesis

Improvement of SPIDER tomographic diagnostic

F. Franco, 2022/2023

GOAL: Improving the reconstruction algorithm and accuracy to estimate the beam current density non-invasively

Modelling and numerical code development



Real data application

Experimental activity

Example of Master Degree's Thesis

4 thesis in 2023, one ongoing

3 PhD students:

Fusion plasmas
- **M. La Matina**, *Electron density profile diagnostics and plasma wall interaction characterization in fusion plasmas*, 2° year
- **L. Cinnirella**, *Diagnostics of confinement properties of fusion plasmas*, 1° year

NBI ←
- **G. Emma**, *Improving the homogeneity of large-size multi-beamlet ITER negative ion sources*, 1° year

- Optical diagnostics can be used to study **very different plasmas**
- Fundamental diagnostics in almost all **fusion devices** and **neutral beam injectors**
- Experimental activity: how **to calibrate**, **operate, validate** and **interpret experimental signals** + **modelling** and **data analysis**
- Development of expertise that can be used in **very diverse areas**: tomography, how to use lasers, numerical codes, ..

https://www.igi.cnr.it/formazione/tesi-laurea/

Contacts

Speaker: margherita.ugoletti@igi.cnr.it
lorella.carraro@igi.cnr.it

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Spectroscopic measurements: UV

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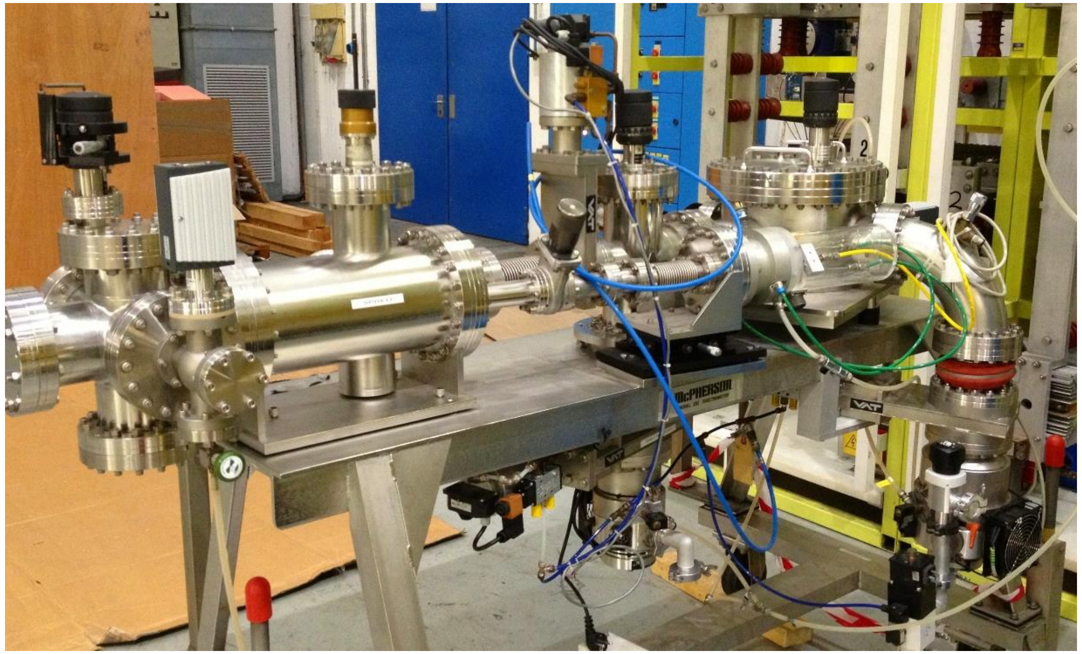


SPRED spectrometer (2105 g/mm)

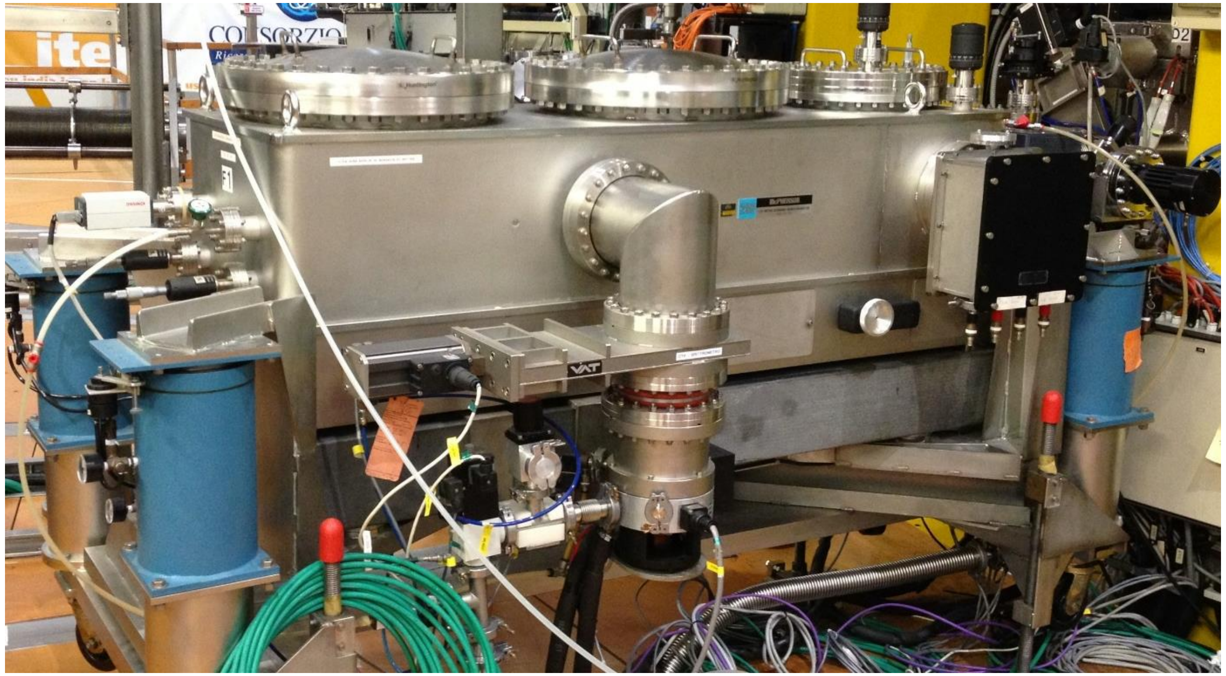
10-110 nm

71° grazing incidence flat field

$T_{e.max}$ $500 - 800\ eV$

$n_{e.max}$ $3 - 4\ 10^{19} m^{-3}$

Monitoring impurity species emitting in the plasma



Vacuum Czerny-Turner spectrometer

120-800 nm

Intensified PD array, 0.25 ms time resolution

Time evolution of He-like ionization states of C^{+4} and O^{+6}, ion temperature measurement in the C^{+4} and O^{+6} emitting region

L. Carraro et al., Nucl. Fusion ***36****, 1623 (1996)*

Not only fusion plasmas: Neutral beam injector applications

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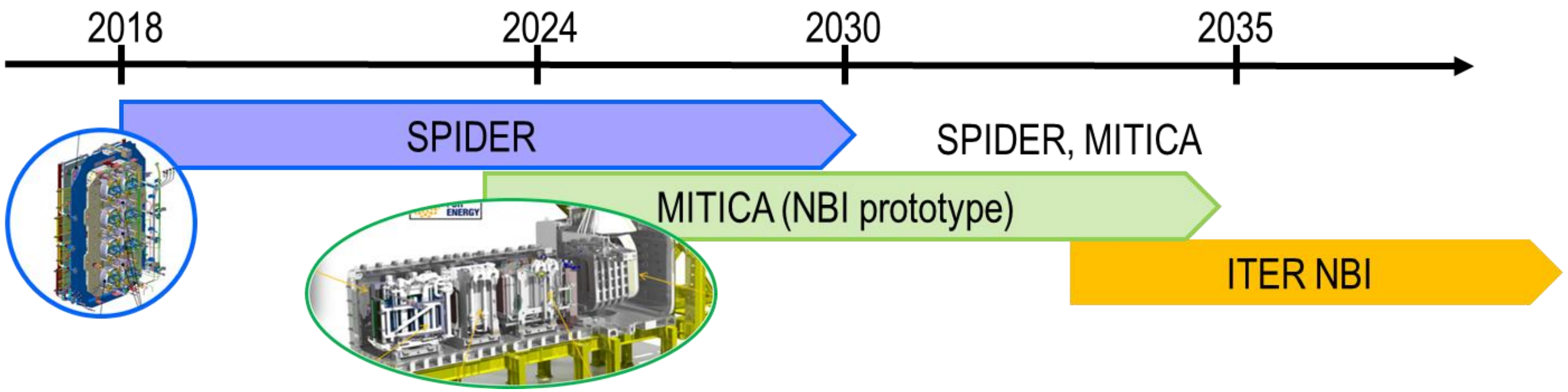
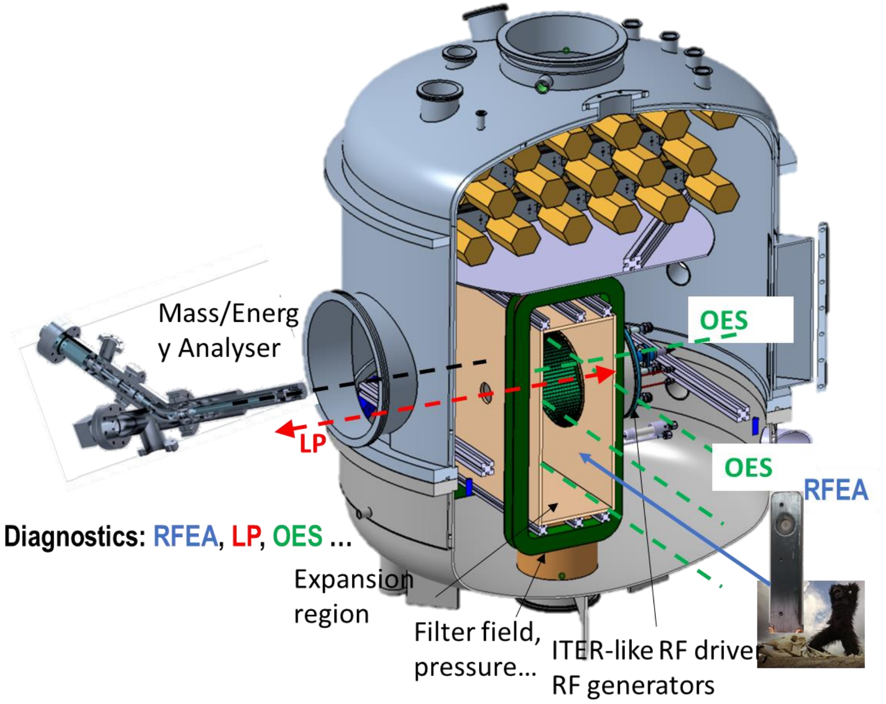
MINION





A **new test bed**, MINION, is operating at Consorzio RFX, Padova aiming at studying an ITER relevant RF-driven plasma.

MINION is equipped with several diagnostics including optical emission spectroscopy, visible cameras, Langmuir probes and other diagnostics with the aim **to characterize the plasma parameters and define the most promising technological advancement for the ITER NBI**.

Contact: isabella.mario@igi.cnr.it

What can you learn from us

"Over the course of my stay at RFX I learned ***how to work as part of a research group****, how* ***to carry out data analysis autonomously*** *and how* ***to present my results to the scientific community****"*

"I had the chance to work in presence and this allowed me to spend considerable amounts of time ***working on the hardware of the diagnostics*** *so I developed* ***useful laboratory skills****"*

"In parallel to the laboratory work and the data analysis I also carried out ***several coding tasks****, aimed to better the existing data analysis routines and thanks to this I learned how to program in IDL and strengthened my coding skills."*

G. Casati, Master Thesis at London Imperial College; title: Characterisation of SPIDER by means of spectroscopic diagnostics

- **Optical diagnostics can be used to study very different plasmas**
- **Fundamental diagnostics in almost all fusion devices and neutral beam injectors**
- **Experimental activity: how to calibrate, operate, validate and interpret experimental signals + modelling and data analysis**
- **Development of expertise that can be used in very diverse areas: tomography, how to use lasers, modelling,..**

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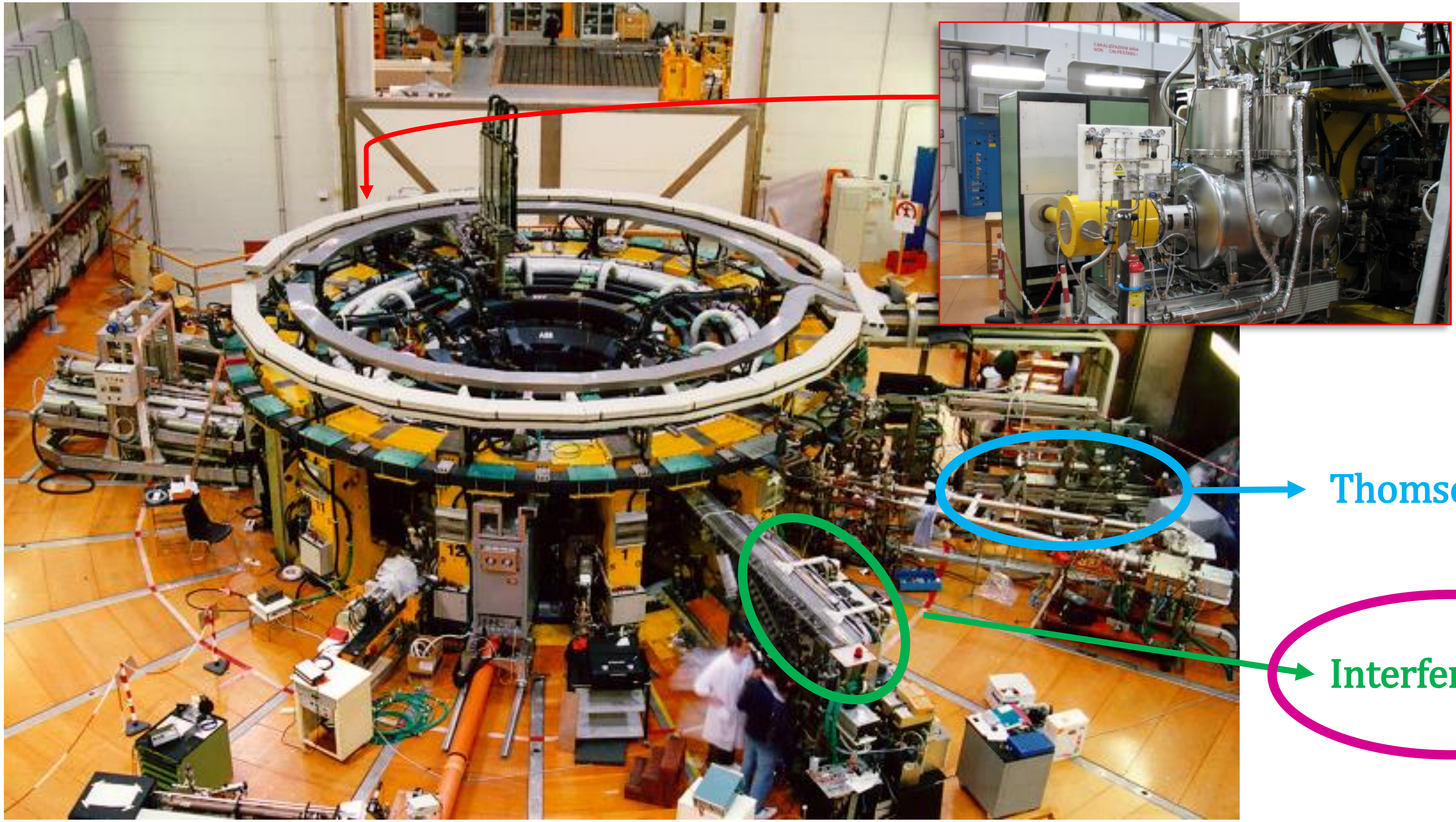
Active diagnostics



Diagnostic neutral beam

Thomson scattering

Interferometer

Active diagnostic: Interferometry for plasma electron density measurements

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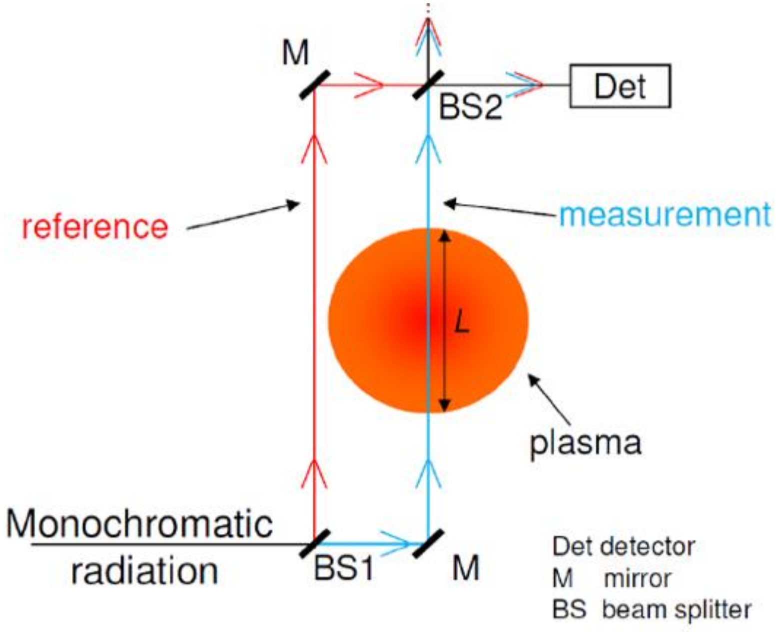

Mach-Zehnder configuration

The interferometric signal due to the superposition of an electromagnetic wave traveling through the plasma and one traveling the same path in vacuum is given by the two wave phase shift, ΔΦ, which depends upon n_e, the plasma electron density, i.e.:

$$\Delta\Phi = 2.82 \times 10^{-15}\lambda \int_{z_1}^{z_2} n_e dz$$

λ: laser wavelength in meters;
z_2-z_1: path traveled by the electromagnetic wave inside the plasma in meters;
n_e: plasma electron density in m^{-3}.

In this work a *dispersion interferometer* *, which is a new scheme of interferometer suitable for compensating vibrations, has been designed and built on the optical bench, testing its working characteristics

* VP Drachev, Yu I Krasnikov, and PA Bagryansky. Review of scientific instruments 64.4 (1993), pp. 1010–1013.

Example of Master thesis: Infrared Dispersion Interferometer for Plasma Diagnostics, M. La Matina **Supervisor**: L. Giudicotti, **Co-supervisor:** D. Fiorucci, A.A. 2021/2022