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LAPSUS: LAboratory Plasma Spectroscopy for Ultraviolet Space

M. Giarrusso[1]

Istituto Nazionale di Astrofisica – Osservatorio Astrofisico di Catania, via S. Sofia 78, Catania, 95123, Italy e-mail: marina.giarrusso@inaf.it

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Abstract. High resolution spectroscopy, the ultimate technique for plasma diagnostics, requires a huge amount of atomic data. The lack of experimental atomic parameters for highly ionized species (mainly emitting in UV), historically due to difficulty in reaching million degree temperatures under controlled conditions, limits our ability to measure the properties of astrophysical plasmas as the solar Corona. Recently, technology has been developed to produce plasma at very different densities and temperatures, often confined into magnetic traps. Spectroscopic analysis of light emitted by these plasma allows to derive and benchmark atomic data. The goal of LAPSUS was to build a $R=\lambda/\Delta\lambda\approx20\,000$ échelle spectrograph covering 70−400 nm to couple to plasma traps. With the aim to measure the lacking data and develop an experimental atomic database for highly ionized species, overcoming the difficulties to interpret spectra of high-temperature astrophysical environments and supporting space missions.

Key words. Instrumentation: spectrographs – Techniques: spectroscopic – Methods: laboratory: atomic – Atomic data – Plasmas – Sun: UV radiation

1. Introduction

High-resolution spectroscopy is the most powerful tool for investigating astrophysical plasmas. It allows to derive information about different cosmic environments by comparing observed spectra with synthetic ones, which are computed using a vast amount of atomic parameters and transition rates. Spectral codes developed to calculate synthetic spectra allow plasma diagnostics on the basis of experimentally well-known atomic data for neutral and weakly ionized species (Kupka et al. 1999), but rely mainly on theoretical calculations for elements in high ionization stages (Bruhweiler 1992).

The accurate knowledge of atomic parameters for highly ionized species represents a necessary step to fully exploit the vast amount of data collected by space missions devoted to study astrophysical plasmas, as well as those obtained from laboratory plasmas for fusion research. Wahlgren (2011a,b) urged spectroscopists and theoreticians to direct their efforts to the improvement of databases from Extreme to Near UV in terms of completeness and accuracy. In fact the lack of experimental atomic databases for highly ionized species prevents the identification of spectral lines from high-temperature plasmas. For example, Curdt et al.

(2004) pointed out that 40% of the ∼500 UV lines emitted by the solar corona and observed by the SUMER spectrograph on board the Solar and Heliospheric Observatory (SOHO, Domingo et al. 1995) were not been identified. Furthermore, the interpretation of observed UV spectral lines, based on theoretical computations of atomic parameters, can be unreliable since the best calculated wavelength values (e.g. GRASP2K, Jönsson et al. 2013) have an accuracy of the order of a fraction of an Å, often insufficient for unambiguous line identifications. Inaccurately computed transition probabilities and electron-ion collisional excitations and de-excitations complicate the interpretation of spectra from hot plasma. In fact, wrong values of atomic data and transition rates propagate down to the determination of plasma parameters, making their understanding difficult and thus hindering progress in a variety of fields (see e.g. Del Zanna & Mason 2018).

The lack of experimental data is historically due to the difficulty of producing laboratory plasmas in stable high-temperature conditions. However, recent advances have allowed plasmas at very different temperatures and densities to be created in the laboratory, which can be maintained in stable conditions even for days. These plasmas provide a unique opportunity to measure the missing atomic data and benchmark the theoretical codes by analyzing plasma emission in the X-ray as well as EUV and UV spectral ranges, obtained with a high-resolution spectrograph. Exploiting this opportunity was the goal of the project described in this paper.

2. The LAPSUS project

LAPSUS (LAboratory Plasma Spectroscopy for Ultraviolet Space) was one of the twelve two-year projects financed by ASI, the Italian Space Agency, (grant "Attività di studio per la comunità scientifica nazionale Sole, Sistema Solare ed Eso-Pianeti" under the ASI-INAF Agreement n.2018-16-HH.0) and started on 1st February 2020 at Laboratori Nazionali del Sud (LNS) of the Istituto Nazionale di Fisica Nucleare (INFN). The project involved researchers from INFN-LNS, Istituto Nazionale di Astrofisica - Osservatorio Astrofisico di Catania (INAF-OACT), Università degli Studi di Catania (UNICT), University of Michigan and University of Cambridge.

SCIENTIFIC GOAL - The final goal of LAPSUS was the building of an experimental atomic database for highly ionized species. For this purpose, it was structured into four Work Packages (WPs): the plasmas under study were planned to be created within the devices available at LNS (WP Plasma Traps, section 2.1). Plasma emission was planned to be observed by an échelle spectrograph (WP UV Spectrograph, section 2.2) working in the range 70 – 400 nm with spectral resolution $R = \lambda/\Delta\lambda \approx 20\,000$, to be designed and built by OACT researchers during the first year of the project. Spectra emitted by a single chemical element turned in plasma (WP Spectroscopy, section 2.3) allow to retrieve the relevant atomic parameters (Ferrara et al. 2024), to include into the CHIANTI atomic database (Dere et al. 1997, 2019) for public distribution (WP Atomic Database, section 2.4).

INTERNAL FACILITIES AND PROJECT MILESTONES - The Internal Special Facilities provided to the project by INAF-OACT were the *échelle spectrograph SARG* (Spettrografo Alta Risoluzione Galileo, 370 – 1000 nm, $R = 164\,000$, Gratton et al. 2001) to simultaneously acquire plasma spectra in the visible range, and the *Optical Laboratory* where the LAPSUS spectrograph was assembled. The Internal Special Facilities provided by INFN-LNS were the *Mechanical Workshop*, and three plasma sources: *Advanced Ions Source for Hadrontherapy, Flexible Plasma Trap, Plasma Reactor* (see section 2.1).

According to the approved activity timetable (Fig. 1), the first year was to be devoted to the development of hardware and software tools necessary to reach the goal of the project. The following milestones were planned:
(1) software development for spectral reduction and conversion of spectroscopic data into atomic parameters;
(2) construction of the UV spectrograph;

(3) construction of the opto-mechanical interface between spectrograph and plasma sources.

The experimental activity was planned during the second year, being the milestones:
(4) acquisition and analysis of plasma spectra;
(5) build of the experimental atomic database for highly ionized species.

Due to the COVID-19 pandemic, LAPSUS suffered a serious delay quantified in one year. Because similar delays had also impacted the other projects, ASI extended the deadline up to one year to allow for the achievement of the objectives. Since INFN-LNS did not accept the extension given by ASI, no milestone of the second year was reached (see section 3 for details).

In the following sections the activity planned for each WP is described in details.

2.1. Work Package: Plasma Traps

Three ion sources at the INFN-LNS were planned for LAPSUS experiments: an Electron Cyclotron Resonance Ion Sources (ECRIS, Geller 1976) called Advanced Ions Source for Hadrontherapy (AISHa, Celona et al. 2019), a simple mirror machine with a flexible magnetic field configuration called Flexible Plasma Trap (FPT, Gammino et al. 2017) and a Microwave Discharge Ion Source (MDIS, Celona 2014) called Plasma Reactor (PR, Gammino et al. 2007). In these devices, designed to feed particle accelerators with beams of highly charged ions (ECRIS) and with high intensity beams of monocharged ions (MDIS), microwaves are injected in plasma chambers filled with the gas to be studied and surrounded by magnets. The momentum of the few free electrons is increased by the microwave field, so that their collisions with neutral atoms lead to the ionization of the gas. The plasma generated is confined in the central part of the chamber by a B-minimum (for AISHa) or a simple mirror (for FPT) magnetic configuration, and can be maintained in stable conditions for days. The plasma confinement time is higher in the AISHa source because of the presence of the radial confining field which allows for the achievement of highly charged ions through the step-by-step ionization process.

Depending on the selected microwave power and magnetic field strength, it is possible to generate plasmas with different electron density n_e and temperature T_e. The FPT is capable of producing and maintaining conditions typical of the solar chromosphere and transition region (see e.g. Byrne 2012; Slemzin et al. 2014), i.e. n_e from 10^9 to 10^{10} cm^{-3} and T_e from 5 to 10 eV ($\sim 5 \times 10^4$ to 10^5 K). Such plasmas present weakly to moderately ionized atoms, e.g. up to O^{3+} or Ar^{5+}. AISHa allows to create and maintain denser and hotter plasmas, with n_e in the $10^9 - 10^{13}$ cm^{-3} range and T_e from 0.1 to 100 keV ($\sim 10^6$ to 10^9 K). The lowest values of density and temperature are typical of the inner regions of the solar and stellar coronae (Byrne 2012; Slemzin et al. 2014). Highly ionized atoms, e.g. up to O^{7+} or Ar^{15+}, had been extracted from AISHa. UV spectroscopy of interest for planetary studies, e.g. the ultraviolet molecular bands observed in Venus atmosphere due to unknown absorbers (for which a proposed mission concept was selected by NASA, Cottini et al. 2018) as well as the emission from Mercury's exosphere that will be acquired by PHEBUS (Mariscal et al. 2019) on Mercury Planetary Orbiter under the BepiColombo mission (Benkhoff et al. 2019), would be also possible by exciting molecules or producing single-ionized atoms inside of the PR. In this device, designed to study the dissociation of complex molecules, n_e spans from 10^8 to 10^{11} cm^{-3} and T_e from 1 to 10 eV ($\sim 10^4$ to 10^5 K).

Plasmas presenting very different conditions can then be created within these devices, making possible the spectral analysis of ultraviolet emission from molecules, neutrals, up to highly ionized atoms. Of great astrophysical relevance are the experiments planned in the EUV spectral range up to $\sim$105 nm, which includes many lines from most stages of ionization of C, O, N, Ne, S, Mg, Si, Fe. These ions are formed in the solar atmosphere at temperatures from 10^4 to 10^6 K and their emission will be observed by the SPICE spectrometer on board the Solar Orbiter (SPICE Consortium et al. 2020).

2.2. Work Package: UV Spectrograph

The first, fundamental task of the LAPSUS project was the construction of a spectrograph to be coupled to magnetic traps in order to measure plasma emission. The four basic requirements for the instrument were 1) high spectral resolution, 2) working in the ultraviolet spectral range, 3) easy to interface to different plasma traps (transportable), and 4) low cost (€ 90 000).

We planned to build an in-vacuum $R \approx 20\,000$ échelle configuration covering the spectral range from 70 to 400 nm in three bands (see below), which overlaps with that of many past and future solar missions. The total length of the instrument was initially thought of about half metre. Optical design, similar to the one of ARAGO (Perea Abarca et al. 2017) and CAOS (Leone et al. 2016) spectrographs, is shown in Fig. 2: the collimator is a spherical mirror of 25.4 mm of diameter. The collimated beam reaches the main disperser, a 26 mm × 51 mm échelle grating with 0.158 lines/μ and blaze angle of 63^{o}, which will redirect it towards the second grating acting as Cross Disperser (C×D). The camera is a spherical mirror cut rectangular 40 mm × 70 mm, and the detector is a back-illuminated 2048 × 2048 pixels CCD with 13.5 μ pixel size. Spectra in the three bands 70 – 100 nm, 100 – 200 nm and 200 – 400 nm were planned to be acquired by inserting a C×D optimized for each one. Some overlapping in spectral coverage between these three bands could be used to facilitate cross calibration. C×Ds work in the first order, so the second order spectra on the CCD is avoided by introducing an ad hoc coated collimator. Simulations locate the "visible spectrum" outside the camera and never pointing to the CCD; also, stray-light was planned to be minimized as in Greggio et al. (2018).

Fig. 3 shows how the instrument was initially thought to be interfaced to plasma devices. An elliptical mirror between spectrograph and plasma trap allows the emitted radiation to reach the slit. The mirror is placed inside of a dewar with the upper and lower walls positively and negatively charged (as a capacitor) in order to deflect any charged particles leaving the trap to avoid damage on the CCD detector. In addition, a cryopump will cool the dewar to stop neutrals leaving the trap, so that only radiation reaches the CCD. In order to perform spectroscopy at wavelengths shorter than 100 nm, the whole spectrograph and the dewar are housed in a vacuum chamber directly linked to the plasma trap without any optical window.

Since below 100 nm the standard hollow cathode lamps cannot be used and the wavelengths of spectral lines are not accurately known, the initial wavelength calibration of the spectrograph was planned at the Elettra Sincrotrone Trieste (http://www.elettra.eu). Synchrotron light is also necessary to determine the absolute efficiency of the instrument as a function of wavelength. The final efficiency of the spectrograph (estimated from geometries and nominal efficiency of optics and detectors) was expected to be of the order of 1%.

2.3. Work Package: Spectroscopy

Laboratory sources, where plasma with stable temperature and density distributions can be created and controlled, provide a unique opportunity to measure and compile a complete list of spectral lines (wavelength and intensity) emitted by, in principle, any atomic element relevant for high energy Astrophysics. These quantities can be used to determine and/or benchmark atomic data useful for the analysis of spectra from any astrophysical source, as well as fusion plasmas.

We planned to introduce the elements under study (listed in section 2.1) into the plasma traps one at a time, solid materials being injected from radially distributed ovens. For each element can be recorded spectra showing lines due to different ionization stages depending on T_e (which can be changed according to the input microwave power). A series of combinations of electron temperature and density was planned to be set in the chambers, with the aim to sample different plasma conditions. Of particular importance is sampling different electron temperature ranges, in order to identify the ionization stages of the element under study.

Furthermore, we planned to measure the emission simultaneously in the UV range

70 – 400 nm (with the échelle spectrograph described in section 2.2) and in the visible spectral range 370 – 1000 nm with the échelle spectrograph SARG. The combination of UV and visible measurements is crucial to benchmark atomic code calculations to an unprecedented accuracy, and to determine atomic parameters.

2.4. Work Package: Atomic Database

As stated before, we planned to carry out atomic data benchmarks on an ion-by-ion case by filling the trap with a single element at a time. Plasma diagnostics to measure the electron temperature and density along the line of sight had to be performed using standard diagnostic techniques described in Phillips et al. (2008) and Del Zanna & Mason (2018). These measured quantities would have been utilized to *1*) compare with the expected density and temperature values inside the plasma chamber, and *2*) benchmark the atomic data and transition rates necessary to calculate the theoretical line intensity ratios used to perform plasma diagnostics itself. The analysis would be carried out in three steps. First, using the intensity of lines emitted from the same upper level to compare the ratios of the Einstein values for each transition; this comparison, in an optically thin plasma, does not depend on the plasma electron temperature and density. Second, comparison between intensity ratios (independent of density) theoretical and observed: it allows a test on the collision and radiative transition rates that contribute to the level population of each of the two levels. Third, use standard diagnostic techniques to determine the distribution of the plasma along the line of sight for each of the selected temperature settings. The obtained distribution would be utilized to calculate synthetic spectra. This is the last step of the comparison, that could be used in two ways: *a*) to verify the agreement between observed and synthetic intensities, providing a further benchmark on the atomic data, and *b*) most importantly, to identify the previously unidentified transitions. Such identifications are fundamental to determine the wavelength of these transitions and to measure from those values the energies of the involved levels. Also, these new identifications allow to carry out the benchmark of the atomic parameters for these newly identified lines for the first time.
The spectroscopic plasma parameters we aimed to obtain through the LAPSUS project would had provided a database of experimental atomic data to be publicly distributed through the CHIANTI code.

3. Results and Critical Issues

LAPSUS started on 1st February 2020 in coincidence with the COVID-19 pandemic, due to which it suffered major delays. During the first year the lockdown has mostly slowed the process of purchasing of the spectrograph components. Important delays also occurred by suppliers in the production of custom pieces. Additionally, the instrument assembly was slowed because of the limited access to the laboratory. So, in the middle of 2021 the accumulated delay was estimated to be of one year. With similar delays affecting the other projects, ASI extended the deadline up to one year. The extension would have allowed LAPSUS to be completed at the end of 2022.
We officially requested to INFN-LNS to take advantage of the ASI extension in order to achieve the project objectives, but the Institute did not accept. LNS also pointed out that the experimental activity of LAPSUS (initially planned to be done during 2021) could not be carried out at LNS in 2022. As a consequence, the project ended on January 2022 and no milestone of the second year was reached.

By referring to the milestones planned for the first year (section 2), the results obtained are reported below.

(1) The software for spectra reduction and conversion of spectroscopic data into atomic parameters was developed (and later used for rare earths by Ferrara et al. 2024). At first, in order to correctly interpret the observed spectral line intensity taking into account the non-insotropic emissivity effects of magnetized plasmas (as in plasma traps), the Zeeman split in polarized light was introduced in the Non-Local Thermodinamyc Equilibrium code

CHIANTI (Giarrusso et al. 2020). The software procedures for spectral line interpretation through CHIANTI were also developed. These procedures were validated on Vacuum-UV (100 – 300 nm) spectra emitted by plasmas of the Frascati Tokamak Upgrade (FTU, Andreani 1993), provided to us by the group of spectroscopy of Divisione di Fisica della Fusione ENEA of Frascati. Fig. 4 shows an example of line identification for Iron (purple spectrum), Oxygen (pink), Chromium (green), and Nickel (blue): the procedures calculate each CHIANTI spectrum by integrating the contribution of emitters taking into account the electron temperature and density distributions within the FTU.

(2) The UV spectrograph was built by the OACT researchers involved in the project (Fig. 5, right). The opto-mechanical design of the instrument was selected for oral presentation at SPIE Optical Design Conference in Madrid on September 2021 (Munari et al. 2021). The spectrograph has a weight of ~ 30 kg, and all its components (described in section 2.2) are placed inside an in-vacuum cilindrical dewar of dimensions 90 cm $\times$ 30 cm. It can be equipped alternatively with two different slits of length $100\,\mu$ and width $40\,\mu$ and $20\,\mu$, respectively.
The instrument was completed at the end of 2021, as expected by taking into account the overmentioned delay. The correct operation was verified through the acquisition, with optical fibers, of the solar spectrum in the visible range (Fig. 5, left), obtained by appropriately rotating the cross-disperser optimized in the range 200 – 400 nm. Comparison with literature data is reported in Fig. 6, showing four portions of the LAPSUS solar spectrum (white) and spectra of the Sun acquired with resolution $R \approx 12\,000$ by the Solar-Stellar Spectrograph at Lowell Observatory[1] (orange). Please note that, despite differences in spectral lines (i.e. depths and blending) due to the highest resolution ($R \approx 20\,000$) of the LAPSUS spectrograph, the wavelengths and equivalent widths are coincident.

Criticality: difficulties were encountered in programming the wavelength calibration of the spectrograph at the Elettra Sincrotrone Trieste, because of the delay in the construction of the instrument as well as the delays in the activities of the Elettra Sincrotrone Trieste due to the pandemic emergency. In 2021 a possible way-out to the wavelength calibration was offered by the ENEA Institute of Frascati. The vacuum sources EUV Xe of the type Discharge Produced Plasma and VUV hollow cathode would have been available to the LAPSUS project if an official agreement had been signed between the involved Institutions.

Also, the researchers of Divisione di Fisica della Fusione ENEA had officially shown interest in using the LAPSUS spectrograph for plasma diagnostics of ENEA sources and then for the determination of atomic parameters, making up for the non-availability of the LNS plasma traps for the year 2022 and giving an alternative to the conclusion of the project. It was discussed a planning of the experimental activity to be carried out in terms of elements to be analyzed, timing of use of ENEA sources, costs for mechanics and gas supply. However, once the instrument was completed and the availability of ENEA sources for calibration and measurements was confirmed for the year 2022, it was not possible to proceed since LNS, after a further official request, declined again the extension given by ASI.

(3) The opto-mechanical interface between spectrograph and plasma sources was not built.

Criticality: the spectrograph-sources interface was necessary for the acquisition of the spectra emitted by the plasma traps. A preliminary mechanical design of the interface was produced by LNS in May 2021 for AISHa, and in November 2021 for PR. However, no interface was built.

[1] http://www2.lowell.edu/users/jch/sss/article.php?r=t_data_specatlas

Work Package (*Responsible*)	***Months from Kick Off*** *ACTIVITY TIME TABLE*			
	1-4	**5-10**	**11-12**	**13-24**
Atomic Database (LNS)	Planning of experimental acitivity. Software development to convert spectroscopic data in atomic parameters			Determination of atomic parameters from spectroscopic data
UV Spectrograph (OACT)	Procurement	Hardware & Software integration Optical alignment	Calibration & Verfication Wavelength calibration at Elettra Sincrotrone Trieste	UV Spectrograph Operativity
Spectroscopy (UNICT)				UV and visible (SARG) Spectroscopy for a total of 900 hours
Plasma Traps (LNS)	Procurement of materials (in kind) to be injected in the Plasma Traps	UV spectrograph and Plasma Traps integration		Plasma Traps operativity

Fig. 1. LAPSUS timetable as planned. The activities shaded in grey were not carried out (see text for details).

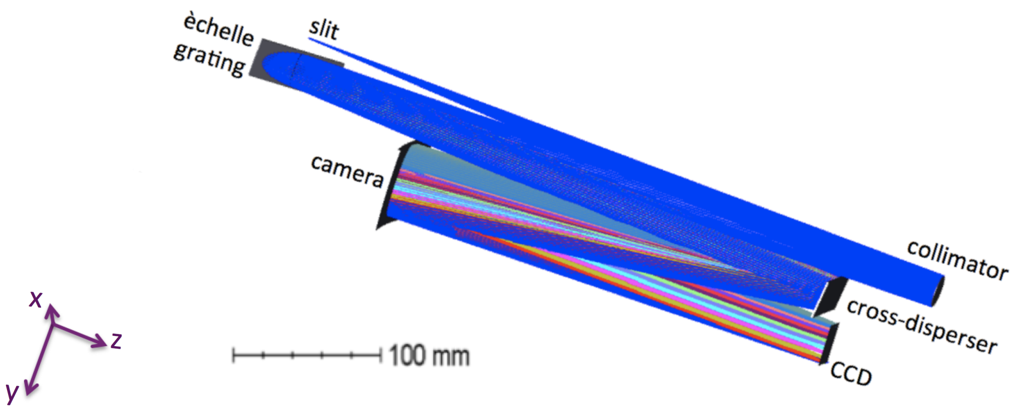

Fig. 2. Optical design of the LAPSUS UV spectrograph.

4. Conclusions

This paper describes LAPSUS, a two-year project financed by ASI. It started on 1st

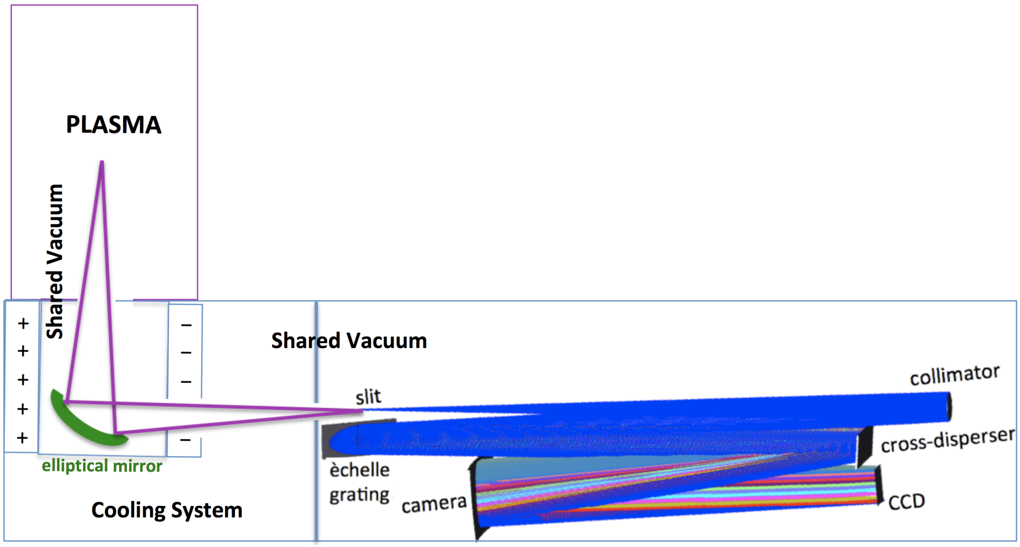

Fig. 3. Schematic design of the interface between UV spectrograph and plasma traps as it was initially planned. Please note that the upper and lower walls of the dewar containing the elliptical mirror are positively and negatively charged, reported as lateral walls in the figure for simplicity. See section 2.2 for details.

February 2020 at INFN-LNS, where UV high-resolution spectroscopy to laboratory plasma emission was planned to be carried out. The aim was to measure the lacking atomic data in order to develop an experimental atomic database for highly ionized species, overcoming the difficulties to interpret spectra of high-temperature astrophysical environments and supporting space missions.

For this purpose a $R \approx 20\,000$ échelle spectrograph covering the range 70−400 nm was built by the OACT researchers involved in the project, and the software tools for spectra reduction and conversion of spectroscopic data into atomic parameters were developed. Acquisition and analysis of plasma spectra were planned during the second year. LAPSUS started in coincidence with the COVID-19 pandemic, due to which it suffered a delay that, in the middle of 2021, was quantified in one year. Since similar delays also impacted the other projects, ASI extended the deadline up to one year. However INFN-LNS did not accept the extension. As a consequence, LAPSUS ended on January 2022 and no milestone of the second year was reached.

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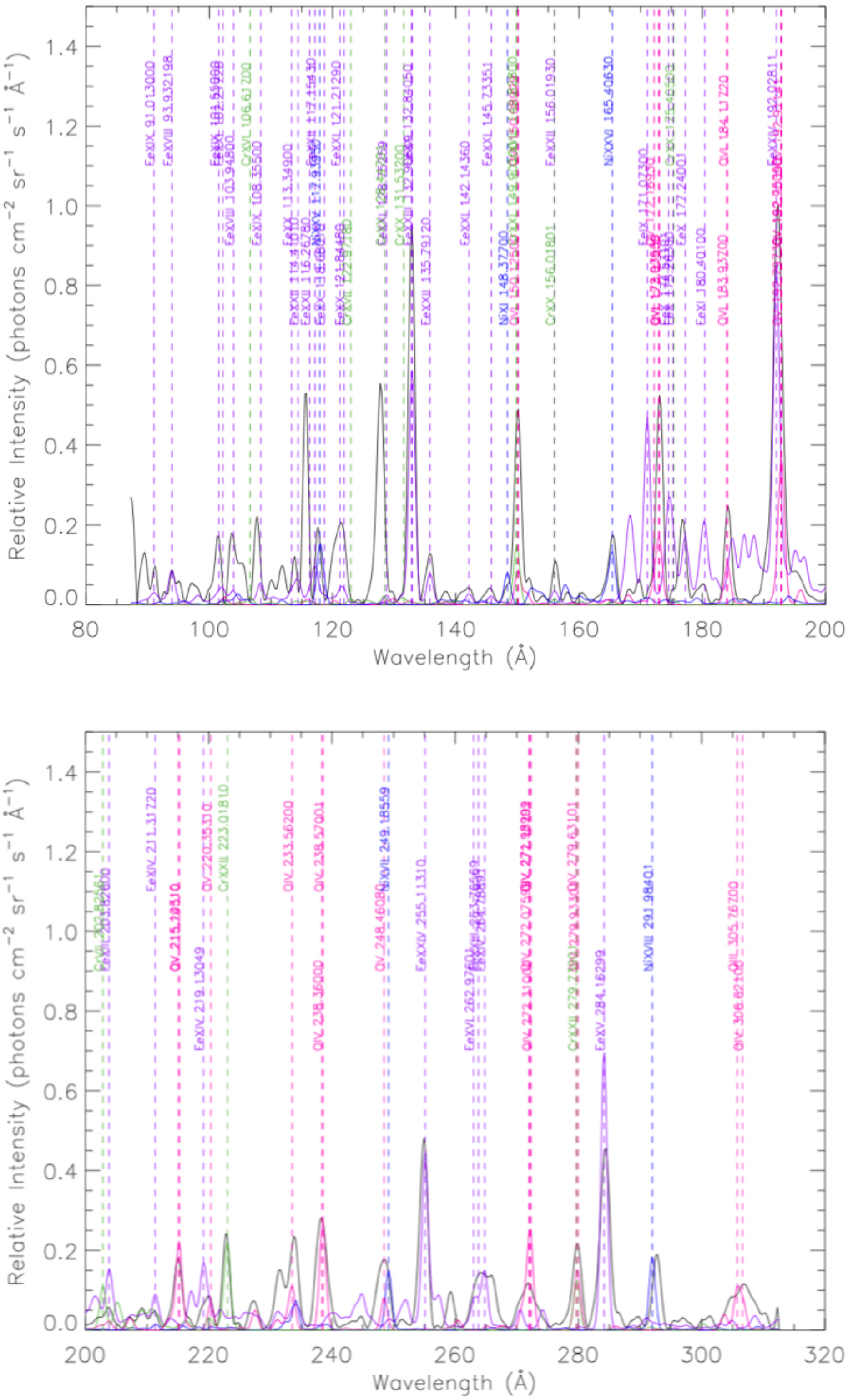

Fig. 4. Example of line identification of a Frascati Tokamak Upgrade spectrum (black) through CHIANTI spectra for Iron (purple), Oxygen (pink), Chromium (green), and Nickel (blue) computed with the procedures developed for LAPSUS. See paragraph (1) of section 3 for details.

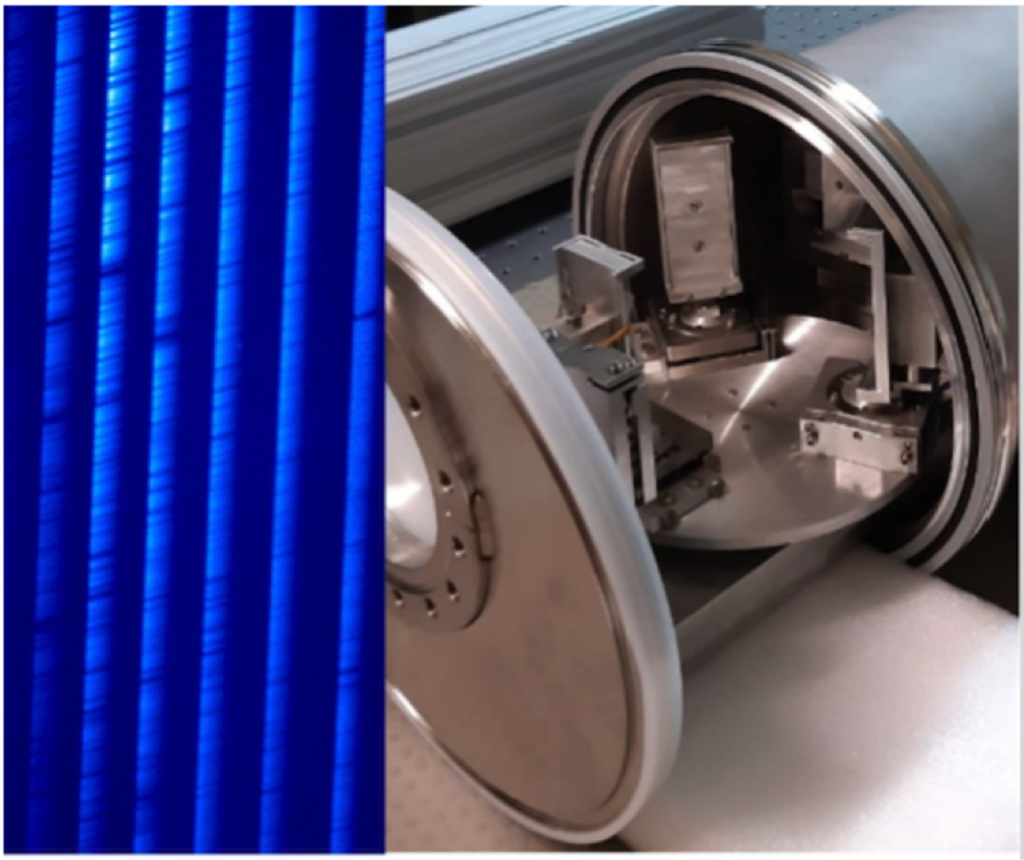

Fig. 5. Right: a picture of the UV spectrograph built at the Optical Laboratory of OACT (cross-dispersers are not inserted). Left: a detail of the CCD showing the solar spectrum acquired with optical fiber in the visible by rotating the cross-disperser optimized in the range 200 – 400 nm.

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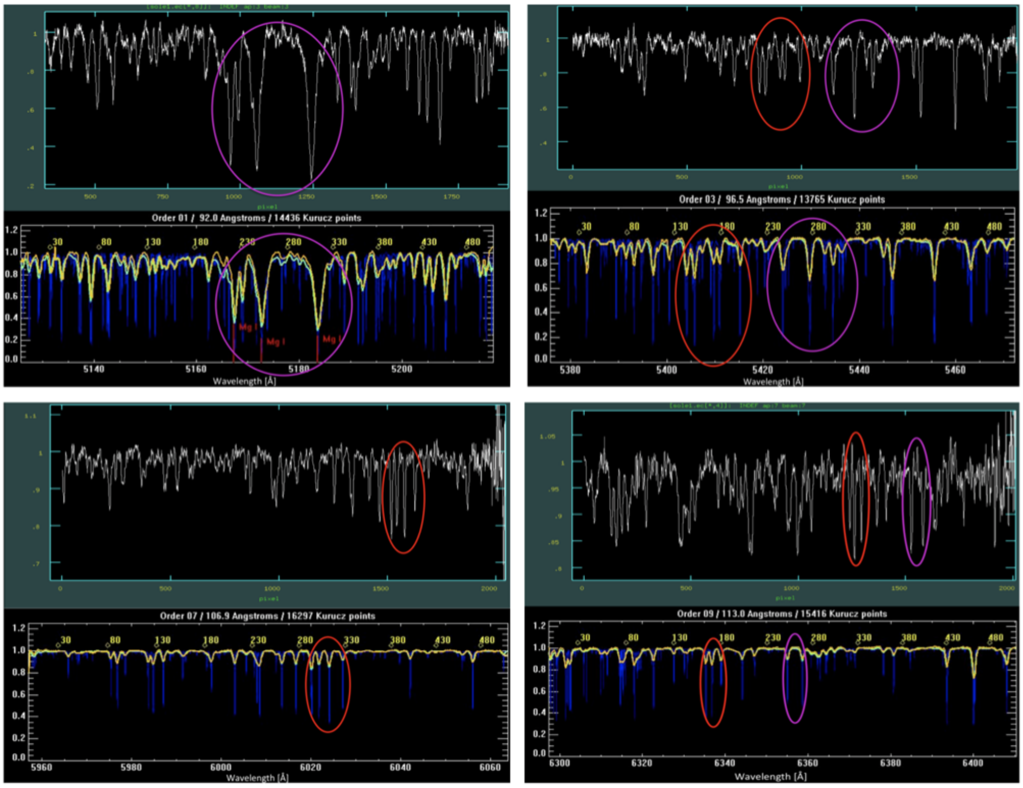

Fig. 6. Portions of the visible spectrum of the Sun acquired with the LAPSUS spectrograph by means of optical fiber (white), compared with literature solar spectra (orange) acquired by the Solar-Stellar Specrograph (SSS) at Lowell Observatory (http://www2.lowell.edu/users/jch/sss/article.php?r=t_data_specatlas). Literature plots include synthetic high-resolution spectra (dark blue), also convolved to the resolution of the SSS (light blue). Red and pink circles highlight the correspondence between some groups of spectral lines. Please note that the LAPSUS spectrum is not calibrated in wavelength. See paragraph (2) of section 3 for details.

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