Atomic interactions in supercritical fields: preliminary investigations for SPARC in-kind contributions

V. Stancalie[1], G. Buica[2], A. Stancalie[1], A. Zorila[1], S. Simion[1], V.Pais[1], C. Iorga[1]

[1]*National Institute for Laser, Plasma and Radiation Phys.,077125 Magurele-Ilfov, Romania*

[2] *Space Science Institute, Magurele-Ilfov, Romania*

Programme	**PN III / Program 5/Subprogram 5.2**
Project type*:*	**FAIR-RO ;** Experiment **SPARC**
Project coordinator:	**INFLPR** -The National Institute for Laser, Plasma & Radiation Physics
Partner:	**I SS** -Institute of Space Science

Planned contract /Value = **1.800.000 lei**:

Outline

- ❑ Motivation & Introduction — INFLPR in-kind contribution to SPARC@FAIR
- ❑ Physics related — Summary of theoretical works performed at the INFLPR in support of SPARC@FAIR
- ❑ The UNIT — Summary of the most important technical parameters of the XUV-storage-ring coupling unit, testing the first prototype at HI Jena, preparation of the first experiments at CRYRING@GSI
- ❑ Selected publications on the subject of the project
- ❑ List of talks of group members
- ❑ Resources and Budget
- ❑ Outlook

Motivation

- The Technical Design Report: SPARC@HERS: Instrumentation, approved by the Expert Committee Experiments (ECE) on 22 Jan 2016, establishes a large group of Institutes, including **the National Institute for Laser, Plasma and Radiation Physics** (INFLPR), distributed over the subjects Laser Spectroscopy, Intense Laser/Ion Interaction and Laser Cooling.
- More than 70 researchers, including the INFLPR researchers are listed as participants for these subjects. The **INFLPR in-kind** contribution is dedicated to design work on the laser beam transport and interaction chamber for the HESR.
- The INFLPR and ISS scientific collaboration within different SPARC working groups started in 2006 (DR and MPI studies)

WP 1.2. High Intensity Laser; WP 3.11. Implementation of a Laser Setup; Theory working group

Time	**PSP code 1.3.1.3.11**			**Costs**
Construction 2007 - 2012	**Investment**	**Experiment Infrastructure**	**Laser set-up**	**200 kE**
	Development of an X-ray laser	Test Experiments at the Reinjection Beam Line	Laser System with High Repetition rate, Installation of Components	**200 kE /2005**

Physics related

Objective 1. The relativistic R-matrix study for state-selective photo recombination cross sections in highly charged heavy ions. Collaboration under WP 1.2 and WP 3.11 (Laser/Ion Interaction Working Groups);
Objective 2. Study of the proof-of-principle experiment dedicated to the investigation of the fine-structure transitions in HCI at HESR. Collaboration under WP 1.2 and WP 3.11 (Laser/Ion Interaction Working Groups);
Objective 3. Investigation of polarization effects in inelastic electron scattering by hydrogen atoms in a laser field.

Theory &simulation

(Collaboration with QUB, ISM (former LIXAM), ITM Kyoto Univ, Inst Adv. En.)

Expertise/INFLPR

- Structure calculation for ITM-TF: R-matrix : RMATXI, RMATX II, Breit-Pauli BPRM, Dirack-Fock theory and method: GRASP, GRASP2K, DARC, Intermediate Coupling Frame Transformation: ICFT, Distorted-Wave -FAC
- Atomic processes in laser field: R-matrix Floquet theory and method

Expertise/ISS

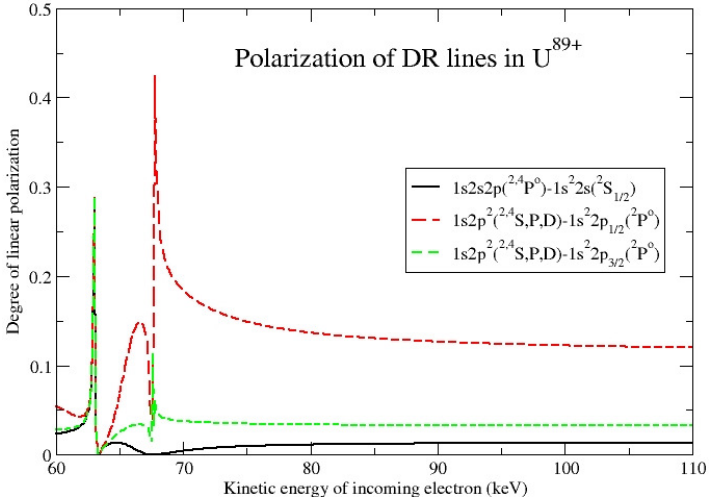
- Multiphoton ionization of two-valence-electron atoms, above-threshold ionization
- Control of atomic processes in electromagnetic fields
- Elastic and inelastic electron- atom scatering in laser fields, FFT

Physics related-Scientific accomplishments *2016-2019 -Summary*

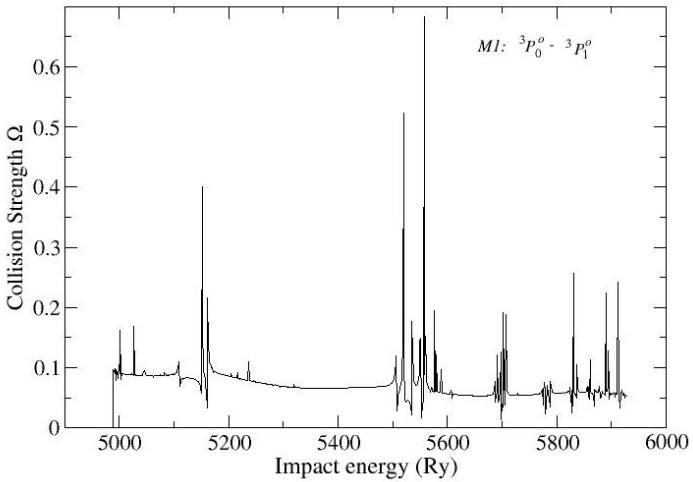
- Relativistic Phase Effect in Modeling Interaction between utraintense laser beams and electrons (EPJ D 2017)
- Energy profiles of the individual photo-recombination cross sections for Be-like ions.
- Photoionization of Al-like ions using the Breit-Pauli R-matrix (BPRM) method (JQSRT 2018)
- Studies on the Electron-Correlation and Relativistic Effects in Target Representation and Low-Energy Collision Calculation (ADNDT 2018)
- Developments in atomic data calculations (JQSRT 2018, ADNDT 2016, 2017, 2018, 2020)
- Studies on the degree of linear polarization, for the dielectronic recombination Kα satellite lines in Li-like W^{71+} to U^{89+} (ADNDT 2018)
- Linear polarization of the dielectronic recombination Kα satellite lines in Li-like Au^{76+} (JQSRT 2019, RJP 2019)
- Photoionization of Mo XXXIII and electron-impact excitation of Mo XXXIV using the Dirac R-matrix method.(ICPEAC2019)
- Investigation of the polarisation effects in inelastic electron-hydrogen scattering by circularly polarized laser field (JQSRT 2016)
- Analysis of the dichroic effects in electron-hydrogen scattering by a two-color circularly polarized (bicircular) laser fields (PRA 2017,ICPEAC2017, PRA 2018, EGAS50)
- Coupling unit testing experiments at HI Jena (collaborative work during working visit) (Vacuum 2020)
- Participation in the preparation of Experiments (FAIR-Phase 0) at GSI, scheduled for the first two weeks last October: The C+ photoionization beamtime experiments at GSI : preparations and installation of the coupling unit plus the laser

Physics related – *Summary of accomplishments*

A. ***The degree of linear polarization*****, for the dielectronic recombination *Kα* satellite lines** in *Li-like* W^{71+} to U^{89+} has been calculated by employing the electric dipole approximation within the density matrix formalism based on the relativistic distorted wave approximations. The effect of Kα satellite transitions on the degree of linear polarization has been estimated as a function of the orbital occupied by the spectator electron. The method account for the interference between intermediate resonance obtained by dielectronic capture for incoming electrons with Gaussian EEDF centered at the threshold energy. The interplay between these high lying resonances is shown to be selectively modified by using different input EEDFs which will induce significant changes for the overall linear polarization of the Kalpha lines. This work represents an extension of the previously calculation performed for the Li-like Au^{76+}.



C. Iorga, V. Stancalie, J.Q.S.R.T.(2019); 224, 206-216: Linear polarization of the dielectronic recombination **Kα** *satellite lines in Li-like Au76+*



V. Stancalie,C. Iorga, X-ray spectrometry 2020; 49(1)pp 42-46 **: X-ray emission via Kα resonance complexes in gold ions.**

B. Investigation of polarization effects in electron scattering by hydrogen atoms in a laser field

- We studied the inelastic scattering of fast electrons by hydrogen atoms, accompanied by the *1s-nl* excitation, in the presence of a *circularly polarized* (CP) laser field, and investigated the polarization effects on the differential cross section (DCS) in inelastic laser-assisted electron-atom collisions.

- We derived, in a semiperturbative approach, a closed analytical form for the DCS, in inelastic electron-hydrogen scattering by a CP laser field, which includes the atomic dressing effects and is valid for both CP and linearly polarized (LP) laser fields.

- We studied the role of the laser field polarization on the DCSs for different scattering geometries where: (i) the laser beam is CP in the (y,z) scattering plane and the laser beam propagates in the x-axis direction, (ii) the laser beam is LP and the polarization vector is parallel to the transfer vector, **q**, and the z axis, respectively.

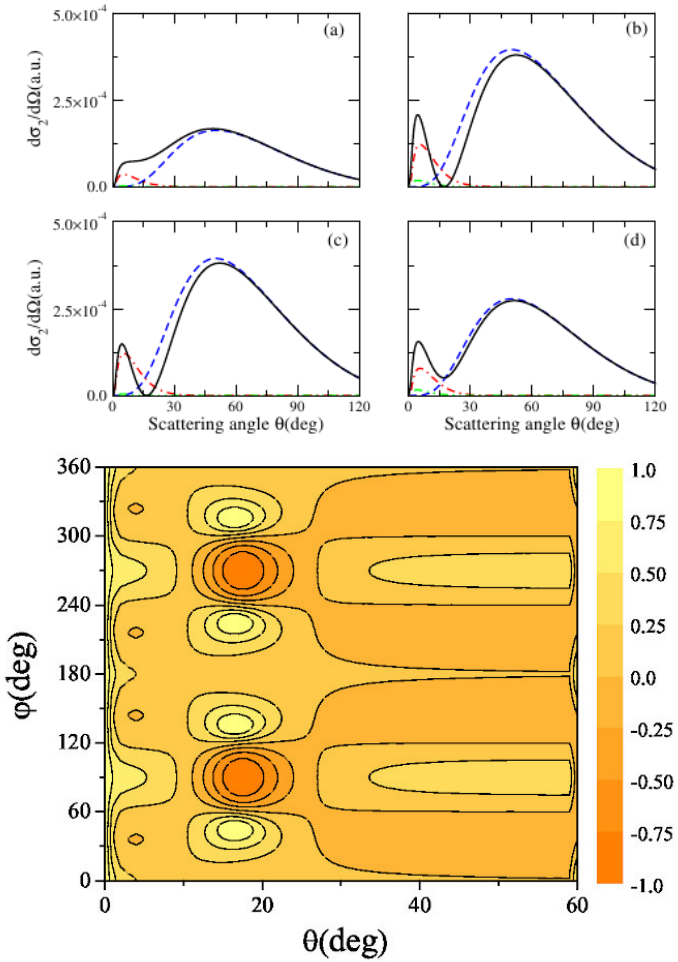
- We analyzed the dichroic effects in elastic electron-hydrogen scattering by a two-color circularly polarized (bicircular) laser fields of commensurate frequencies and moderate intensities for fast projectiles. We have obtained useful analytical formulas for two-photon circular dichroism in angular distributions that give more physical insight into the scattering process and valuable information for experimental investigations.

- The analytical formulas obtained for co- and counter-rotating polarizations in the weak laser field limit, indicate that the two-photon DCS is related to the interference of different quantum paths involving two photons with identical or different polarizations, and by varying the intensity ratio of the co- and counter-rotating two-color CP laser field components we can manipulate the angular distribution of the scattered electrons.

Physics related – *Summary of accomplishments*

B. Investigation of polarization effects in electron scattering by hydrogen atoms in a laser field

- We *predicted the existence of a nonlinear dichroic effect in DCS* at high scattering projectile energies, which is sensitive to the photon energies and laser field intensities.
- The *dichroic effect* in the angular distribution of scattered electrons originates from the nonzero atomic dressing at small scattering angles, whereas at large scattering angles the dichroic effect occurs from the projectile contribution to the scattering signal.



*The total **two-photon DCSs** (full lines) by two-color left- and right-handed-CP laser fields in panels (a) and (c) and two-color left-handed-CP laser fields in panels (b) and (d) as a function of the scattering angle. The azimuthal angles are 90º in panels (a) and (b), and 45º in panels (c) and (d). The photons energies are 3 and 9 eV, 100 eV incident electron energy, the scattering angle 5º, and laser intensity 1 TW/cm².*

- We established that at UV photon energies and small scattering angles there is a clear enhancement of the DCS for corotating compared to counter-rotating laser fields because of the strong atomic dressing effects.

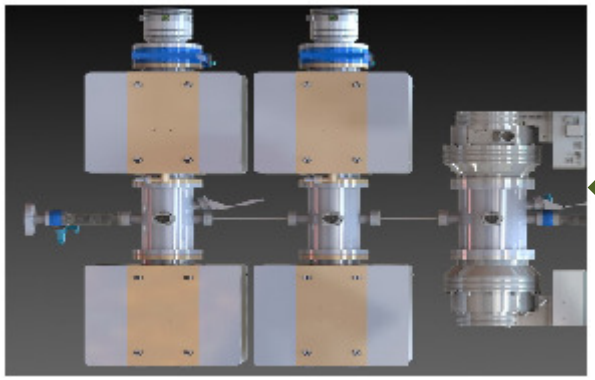
*Contour plot presenting the relative **circular dichoism** of the scattered electrons as a function of the scattering and azimuthal angles, at photon energies of 3 and 9 eV, for two photon absorption, at 100 eV incident electron energy, and laser intensity of 1 TW/cm².*

The UNIT

The *vacuum unit* comprises an efficient multi stage pumping system to decrease the absolute pressure along three stages from 1.5 10^{-5} mbar to < 1.0 10^{-11} mbar. An open aperture of 10 mm diameter guarantees lossless XUV transport to the storage ring target ions.

- Vacuum chambers
- Vacuum pumps and controllers including security shut down system
- Mechanical support frame for mounting at beam height
- Pressure measurement system for all chambers
- Adjustment system for below mounted in-flange tubes
- Heater blankets

Laser out



Laser in

The first chamber, connected with the laser source, has only turbo pumps. The next two chambers seen on the left part of the figure, have both turbo pumps and ion pumps for deepest pressure. The vacuum chamber of the laser source itself is vacuum pumped, but in the current state is not connected with the three chambers

The UNIT: TECHNICAL SPECIFICATIONS

- Input pressure : < 10^{-6} mbar, mainly Argon or Krypton
- Outlet pressure: < 10^{-11} mbar
- Max. heating temperature of whole system: 300 ^{o}C
- Chamber material : corresponding to the requirements of 10^{-11} mbar
- Surface quality: idem
- Clear aperture diameter for XUV beam : 10mm adjustable to the beam axis
- Max size: length < 1.2 m (as short as possible), height < 0.5 m, depth < 0.5 m
- Max weight 500kg
- Max electrical power consumption: 5kW
- Max cooling water heat load: 2kW

- Coupling unit and XUV source setup for tests: **mid of 2017 !**
- Whole system ready for experiments at CRYING: **end of 2017 !**

The UNIT :

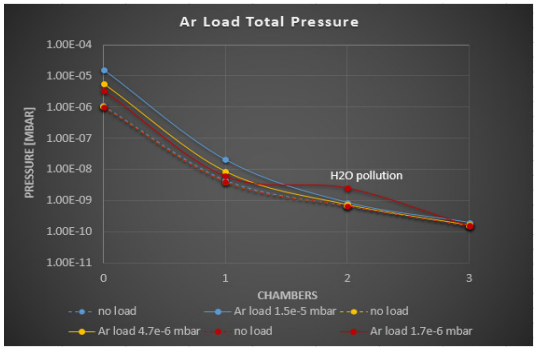
C. Testing the first prototype for a coupling unit developed at HI Jena (Feb-March 2019)

D. Preparation of the first experiments at CRYRING@GSI (Sept-Oct 2019)

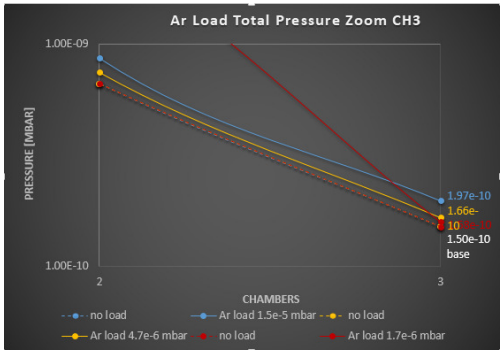
A) Analysis of the UHV in a coupling unit prototype with Restgasanalyzer;

B) Test of a coupling unit prototype with additional gas load (Argon);

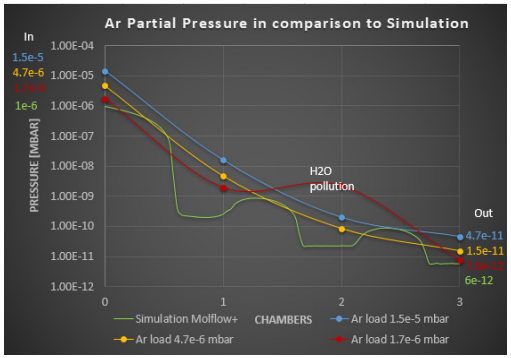
C) Comparison of B) with Monte-Carlo simulation. For optimal results, the chambers were subjected to controlled heating. Heating combined with eliminating the leakages, helped us reach values up to 7.10^{-12} mbar. Finally, a Monte Carlo simulation was performed, based on an exact model of the system design, in order to a) check the influence of argon against all vacuum chambers in order to reproduce the presence of the mirror chamber connected to the system b) compare Monte Carlo simulations to the real measurements. The results show that the numerical models are in good agreement with the experimental data.



Argon load total pressure



Values obtained in the third chamber of the UHV coupling unit



The simulations in agreement with experimental data

M Tschernajew, P Gierschke, H Lin, V Hilbert, J Kurdal, A Stancalie, **J Limpert, J Rothhardt**, Vacuum 2020: 178: 109443
"Differential pumping unit for windowless coupling of laser beams to ultra high vacuum".

Selected publications on the subject of the project

1. **G. Buica,** *Polarization dependence in inelastic scattering of electrons by hydrogen atoms in a circularly polarized laser field,* **J. Quant. Spectrosc. Radiat. Transfer, 187, 190-203 (2017).**
2. **G. Buica,** *Symmetries in elastic scattering of electrons by hydrogen atoms in a two-color bicircular laser field,* **Phys. Rev. A, 96, 043419 (2017).**
3. **A. Popa, V. Stancalie,** *Relativistic Phase Effect in Modeling Interaction between utraintense laser beams and electrons*, **Eur. Phys. J. D. 71:166 (2017).**
4. **V. Stancalie,** *Photoionization of S^{3+} using the Breit-Pauli R-matrix method,* **J. Quant. Spectrosc. Radiat. Transfer, 205, 7-18 (2018).**
5. **G. Buica,** *Circular dichroism in angular distribution of electron-hydrogen scattering in a two-color bicircular laser field*, **Phys. Rev. A, 98, 053427 (2018).**
6. **C. Iorga, V. Stancalie,** *The study of the core-valence and core-core correlation effects on the radiative properties along the magnesium isoelectronic sequence* , **ADNDT 123-124 (2018) 313-328.**
7. **C. Iorga, V. Stancalie,** *Atomic data and line intensities for the S V ion*, **ADNDT115-116 (2017) 1-285** .
8. **C. Iorga, V Stancalie,** *Theoretical investigation of X-ray lasing in argon by photo-ionization from K and L shells*, **Rom. J. Phys. 64, Nr.1-2 (2019)**
9. **C. Iorga, V. Stancalie,** *Linear polarization of the dielectronic recombination Kα satellite lines in Li-like Au^{76+},* **J. Quant. Spectrosc. Radiat. Transfer, 224, 206-216 (2019).**
10. **V. Stancalie, C. Iorga,** *X-ray emission via Ka resonace complexes in gold ions*, **X-ray Spectrometry, 49(1) 42 (2020).**
11. **M Tschernajew, P Gierschke, H Lin, V Hilbert, J Kurdal, A Stancalie, J Limpert, J Rothhardt**, *Differential pumping unit for windowless coupling of laser beams to ultra high vacuum,* **Vacuum 178: 109443 (2020).**
12. **G. Buica,** *Comment on 'Two-photon laser-assisted electron scattering on hydrogen atom"*, **Journal of Physics B: Atomic, Molecular and Optical Physics, Volume 53, Number 15, (2020).**

List of talks of group members (title, conference or meeting, date)

1. *Symmetries in elastic scattering of electrons by hydrogen atoms in two-color bicircular laser fields*-Poster, International Conference on Multiphoton Processes (ICOMP) XIV, Budapest, September 2017;
2. *Studies on the electron-correlation and relativistic effect in target reprezentation and low-energy collision calculation*, IAEA Technical Meeting, December 2016.
3. *Detailed relativistic electron excitation cross sections. Effect of the electron-electron correlation at low energy electron scattering*, the 7-th Conference on Elementary Processes in Atomic Systems, Czech Republic, June 2017.
4. *Photoionization of C+ ions at CRYRING, J Rothhardt,* 15th Topical meeting of SPARC collaboration, Sept 2018 .
5. *X-ray emission via Kalpha resonance complexes in gold ions,* Highly Charged Ions, HCI Conference, Lisbon, Sept, 2018.
6. *Photoionization of MoXXXIII and electron-impact excitation of MoXXXIV using the Dirac R-matrix method, XXXI* International Conference on Photonic, Electronic and Atomic Collisions, ICPEAC , Deauville, France, July 2019.
7. *Circular dichroism in electron-hydrogen scattering in a two-color bicircular laser field,* Poster, European Group on Atomic Systems (EGAS50), Krakow, July 2018

Resources and Budget

2016: 133.800 lei (INFLPR – 90.315; ISS – 43.485)
2017: 704.600 lei (INFLPR – 469.740; ISS – 234.860)
2018: 692.100 lei (INFLPR – 461.400; ISS – 230.700)
2019: 269.500 lei (INFLPR – 178.545; ISS – 90.955)

Value = **1.800.000 lei**

Year	Planned	Committed
2016	133.800,00	133.800,00
2017	704.600,00	1.048.614,00
2018	692.100,00	348.086,00
2019	269.500,00	269.500,00
Contract value	**1.800.000,00**	**1.800.000,00**

Resources and Budget

Budget breakdown (lei, for entire project):

2016-2019

Budget chapter (expenses)	Planned	Committed
Personnel	1.393.375,0	1.238.649,0
Logistical	17.025,0	228.359,10
Travel	31.000,0	17.384,72
Indirect	358.600,0	315.607,18
TOTAL	1.800.000,0	1.800.000,0

Logistics: Equipments, stocks, third party services

Travel: CEPAS 2017, HCI Conf 2018, ICPEAC Conf 2019, EGAS50 2018, ICOMP 2017

Personnel: 2 x Scientific Researchers (SR) 1st degree, 3 x SR 3rd degree, 2 x SR

CO: Equipments	Value (lei)
1. Computer, i5, licence MS Office	1. 1500; 400
2. Vacuum chamber with optical breadboard floor	2. 28.100,0
3. Turbo Pump	3. 96.236,0
4. Pre-pump: Tri-Scroll TS600-W	4. 34.590,0
5. Pressure gauge FRG-700 FULL RANGE PIRANI/IMG G.A., 2.75CF	5. 5.880,0
6. XY stages + bellows + tube	6. 50.109,0
	Total CO: 216.815,0
P1: Equipments	Value (lei)
1. Computer, i7, Win10 license	1. 8159,0
2. MS Office license	2. 989,99
	Total P1: 9,148.99

Outlook

Present and Further collaborative work (2020-2022):

1. The results obtained in testing the prototype differential coupling unit at HI Jena, as well as the tests performed during the preparation of the experiments at CRYRING@GSI (coupling unit +laser), helped us finalize the complete list of components and their prices so that the in-kind contribution can be fulfilled.
2. The experiment of G-PAC Proposal E129 '*Photoionization of C+ ions at CRYRING*' was setup in October 2019. During the experiment plenty of major tasks were achieved. Unfortunately, it was interrupted due to severe vacuum incident. Therefore, the original proposal together with a short supplement has been resubmitted for the call on 10th June 2020.
3. The new proposed experiment '*Probing ultra-short-lived excited states in Be-like Carbon at the ESR*' is proposed to be performed at ESR, and will strongly benefit from the previous experiments performed with the XUV laser at ESR in 2019 and 2020. The XUV source and the Ultra-High-Vacuum coupling unit will be moved to ESR. The preparation phase includes tests of the vacuum system and the XUV laser source control system. *Our group is involved in the proposed experiment.*

Thank you for your attention,