REVIEWS OF TOPICAL PROBLEMS

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X-ray and vacuum ultraviolet spectroscopy at Lebedev Physical Institute (LPI)

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Contents

Abstract. The last third of the 20th century was marked by the rapid development of X-ray and vacuum ultraviolet (VUV) spectroscopy of multiply charged ions. At Lebedev Physical Institute (LPI) this research commenced as studies of X-ray solar radiation and radiation of multiply charged ions in laser-produced plasma. Subsequently, they were supplemented by the study of fast electric discharges and work on X-ray/VUV optics. The formulation of many studies was also motivated by the need for spectroscopic diagnostics of high-temperature plasma and the possibility of developing lasers in the soft X-ray (SXR) range based on transitions of multiply charged ions. The methods of SXR/VUV spectroscopy have found application in the development of new X-ray optical elements and diffraction spectrometer systems. The review notes the main participants in these studies and the main milestones in the development of spectroscopic research at the LPI in the vacuum region of the spectrum, starting from the mid-1960s, and briefly considers the development of the experimental technique used. The review does not claim to be complete, and the selection of cited materials reflects the scientific interests of the author.

Keywords: vacuum spectroscopy, X-ray solar radiation, laser plasma, multiply charged ions, vacuum spectrometers, X-pinch, X-ray optics, multilayer mirrors, VLS grating, X-ray projection lithography, X-ray prism spectrographs

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1. Introduction. LPI: Polyphysical Institute

The P N Lebedev Physical Institute (LPI) was seen by S I Vavilov, the first director of the LPI, as a polyphysical institute in which new domains in modern physics could originate and develop. To a large extent, the formation of new scientific domains and diversification of research over the past six decades have been fostered by the advent of quantum generators of electromagnetic radiation, masers and lasers, for which Soviet scientists N G Basov and A M Prokhorov, together with Charles (USA), were awarded the Nobel Prize in Physics (1964). As shown in this review, high-power pulsed lasers have played and continue to play an important role in the development of X-ray and vacuum ultraviolet (VUV) spectroscopy and the physics of multiply charged ions, as well as in applied areas: the development of X-ray/VUV optics and the making of optical-spectral devices for the vacuum range of the electromagnetic spectrum.

2. S L Mandelstam: initiator of X-ray solar spectroscopy

The study of short-wavelength solar radiation commenced on the initiative of Sergei Leonidovich Mandelstam,[1] head of the Spectroscopy Laboratory of the LPI. Sergei Leonidovich closely followed the progress of research into short-wavelength ultraviolet solar radiation, noting its paramount importance "for both the physics of the Sun and the physics

[1] The author of this review paper passed his first test 'at the base institute' in 1968 under S L Mandelstam, then head of the Department of Optics at MIPT based at the LPI.

of the Earth'' [1, 2]. In the USSR, the study of short-wavelength parts of the spectrum absorbed by the terrestrial atmosphere began after it became possible to move equipment beyond Earth's atmosphere using rocket and space technology. In 1965, a start was made on experiments to record spectra using diffraction gratings and Bragg crystals. The first photograph of an X-ray spectrum down to 9.5 Å was obtained in 1965 during the launch of a diffraction spectrograph on a high-altitude rocket [3, 4].

Subsequent studies of the spectra were carried out in 1969–1983 using photoelectric spectrometers with Bragg crystals installed on 10 spacecraft (Intercosmos series satellites, Vertical' geophysical rockets), which were launched within the framework of the Intercosmos international cooperation program [5, 6]. In these experiments, solar spectra were recorded up to a wavelength of 1.7 Å with a resolving power of up to 10^4. The general scientific supervision of solar radiation measurements was carried out by S L Mandelstam. Spectrometers for the wavelength range from 5 – 20 Å and Bragg quartz spectrometers for the wavelength range of 1.7 – 1.95 Å were developed under the leadership of I A Zhitnik. Apart from S L Mandelstam and I A Zhitnik, the group included I L Beigman, L A Vainshtein, B N Vasiliev, V D Ivanov, V V Krutov, I P Tindo, and A I Shurygin. Crystals of beryl (to record the lines of the Ne IX ion), quartz (Mg XII), ADP (Si XIII, Mg XI), Si (Si XIV), Ge (Si XIV), and NH_4AP (Mg XI) were used [6].

The results of these experiments were reported at the scientific sessions of the Department of General Physics and Astronomy (DGPA) and the Department of Nuclear Physics of the USSR Academy of Sciences on September 29–30, 1971, the DGPA on April 23, 1975, and the DGPA on January 31–February 1, 1979 [7–9]. The first report [7] presented a section of the spectrum of the X-ray flare of November 16, 1970 near 1.8 Å with lines of He- and Li-like iron ions and noted that the spectra of Fe XXIII–Fe XXV ions had not yet been reliably obtained at laboratory facilities. Therefore, the lines were identified by comparison with theoretical calculations of wavelengths performed by U I Safronova. Subsequently [8, 9], the X-ray solar spectra were compared with the spectra of a low-inductance vacuum discharge and laser-produced plasma (Fig. 1). Notably, the excitation of the spectra of multiply charged iron ions in a vacuum spark [10], krypton in the range of 65 – 110 Å [11], and sulfur ions SIX, SX in the range of 175 – 265 Å [12] in a theta pinch. A domestic DFS-6 grazing incidence spectrograph was used to record the spectra.

It is noteworthy that NIIKhIMFOTO developed domestic photographic materials for recording VUV and X-ray radiation. At the LPI, a series of studies by V G Movshev, A N Ryabtsev, and N K Sukhodrev was devoted to their study as well as a comparison with foreign analogues [13–18]. The dependence of the characteristic curves on the angle of radiation incidence on the emulsion layer was studied. Using an ionization chamber, an absolute calibration of the sensitivity of UF-2T photographic films (manufactured by NIIKhIMFOTO) and SC-5 (Kodak–Pate) was carried out in the range of 460 – 1500 Å, as well as UF- 2T, UF-R, and SC-5 in the range of 1.5 – 23.6 Å. It was found that deviations from the law of reciprocity in an AgBr-based emulsion cease to manifest themselves when the photon energy exceeds 8–11 eV.

It was also noted that ''... A laser spark formed on a target in a vacuum should be regarded as one of the most fortunate sources of spectra excitation for our purposes'' [8].

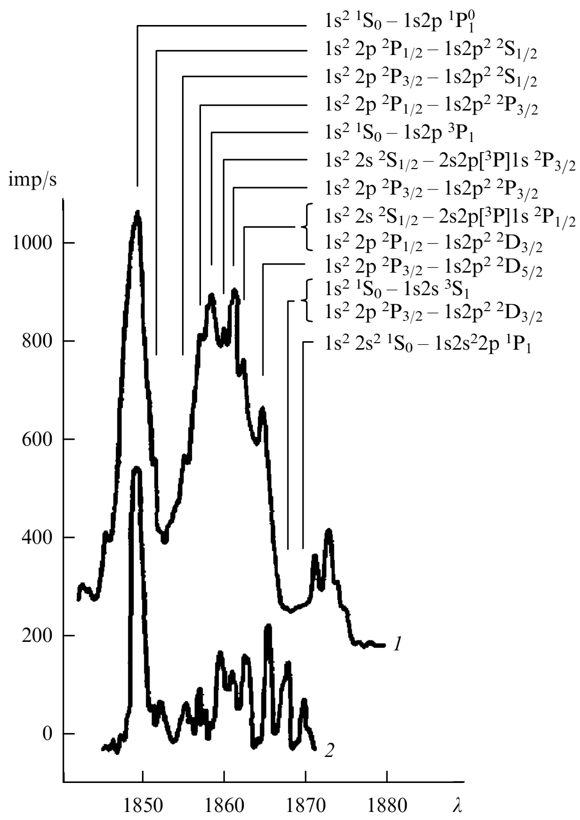

Figure 1. Spectra of iron in region of FeXXV resonance line. *1* — lineout of laboratory spectrum. *2* — X-ray solar flare (16.11.1970, $01h_{01}$mUT, Interkosmos-4) [8]. Wavelengths are given in units of 10^{-3} Å.

The use of laser plasma as a source of line and continuous spectra of multiply charged ions dates back to the mid-1960s. Apparently, the first work in this area was by Ehler and Weissler [19] and Brian Fawcett et al. [20]. The first LPI work was conducted jointly with the Laboratory of Spectroscopy and the Laboratory of Quantum Radiophysics, headed by Nikolai Gennadievich Basov [21, 22]. Employed in these studies was a neodymium glass laser with a pulse energy of 10 J and a half-maximum duration of 15 ns. Q-switching was carried out by a Kerr cell. A DFS-6 vacuum spectrograph with a 1-m-radius grating, mounted at a grazing angle of 8°, was used to record the spectra. Line spectra of AlVI–AlXI ions and spectra of CaXII–CaXVI ions were obtained, arising from $2s^22p^n$–$2s2p^{n+1}$ transitions ($n = 1 - 4$) in the range of 120 – 240 Å. A number of calcium lines were identified for the first time (Fig. 2).

3. X-ray solar astronomy under I I Sobelman

In 1968, the Institute of Spectroscopy (ISAN) was set up as part of the DGPA of the USSR Academy of Sciences. The founder of the institute and its director for the first 20 years was S L Mandelstam. Together with him, some of his students (E Ya Kononov, A N Ryabtsev) also transferred to ISAN. S L Mandelstam also retained supervision of the Laboratory of Spectroscopy of the Lebedev Physical Institute until 1984. At ISAN, the spectroscopy of multiply charged ions enjoyed extensive development within the Department of Atomic Spectroscopy. A significant part of modern data on the wavelengths and energy levels of

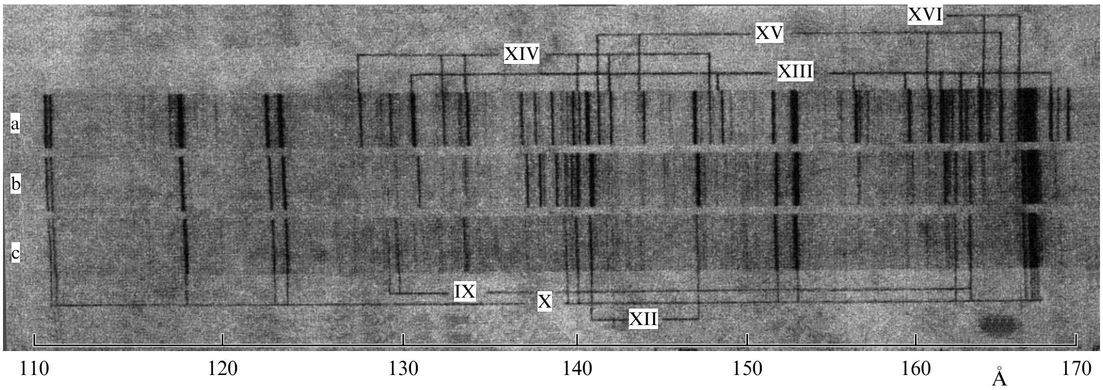

Figure 2. Spectrograms of calcium under different conditions of laser beam focusing. Focal spot diameter: (a) 0.1 mm, (b) 2 mm, (c) 6 mm [22].

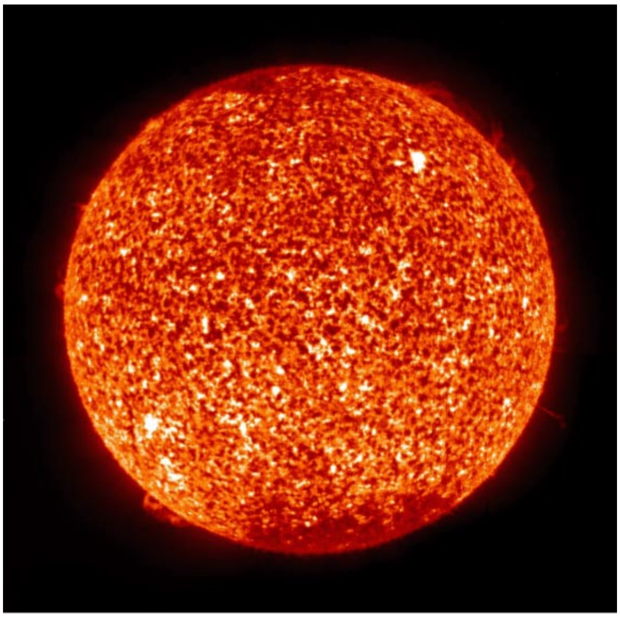

Figure 3. Image of the quiet Sun taken in the 304 Å resonance line of He II ion (a telescope with a multilayer Mg/Si mirror synthesized at the Institute for Physics of Microstructures, RAS) from an Earth satellite on March 1, 2009. Angular resolution is 1.7″ [23].

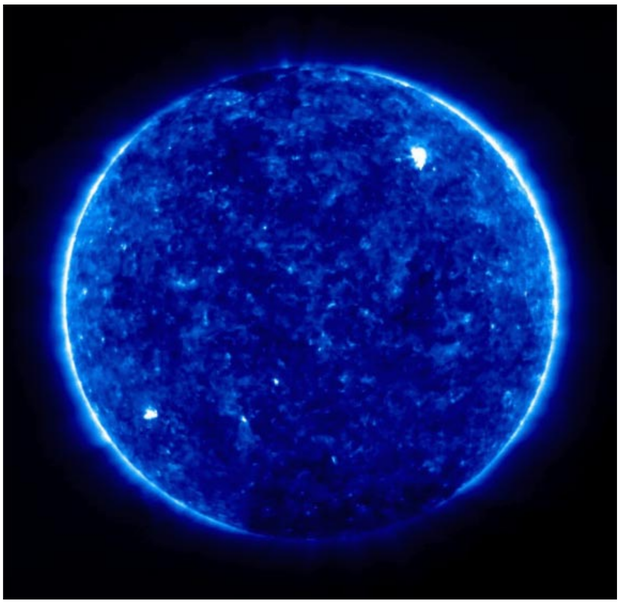

Figure 4. Solar image (Al/Zr multilayer mirror, IPM RAS) in the FeIX line (171 Å) taken from an Earth satellite on March 1, 2009 [23].

multiply charged ions was obtained in the work by ISAN staff members.

In 1984, the supervision of the Spectroscopy Laboratory, and after 1989 the entire Department of Optics, passed to Igor Il'ich Sobelman. Under his leadership, 'Space Line' continued its successful development. In this regard, mention should be made, first of all, of the spectral instruments on the CORONAS series spacecraft (Complex Orbital Near-Earth Observations of Solar Activity), developed under the leadership of I A Zhitnik and S V Kuzin. The first of them, CORONAS-I, was launched in 1994 and operated in orbit until 2001. Launched at the same time, in 2001, was the next satellite, CORONAS-F, which completed its work in December 2005. In February 2009, the CORONAS-Photon satellite with LPI equipment began to operate successfully. The SPIRIT and TESIS equipment installed on the CORONAS-F and CORONAS-Foton satellites were multichannel VUV spectral telescopes-coronagraphs intended to record the solar corona in the ranges of 175 Å (FeIX-XII) and 304 Å (HeII) using multilayer X-ray mirrors (Figs 3, 4) [23], as well as spectroheliographs for the same spectral ranges. The idea of such a spectroheliograph was expressed back in the late 1980s in connection with the possibility of constructing dispersed spectral images of the Sun [24, 25]. Its optical configuration (Fig. 5a) comprises a plane grazing-incidence diffraction grating and a normal-incidence focusing multilayer mirror. Due to the fact that the grazing angle of diffraction in the inside order is several times greater than the grazing angle of incidence, dispersed solar images in individual spectral lines turn out to be highly compressed in the direction of dispersion. An example of such a spectroheliogram is shown in Fig. 5b [26]. The developers of the flight version of the spectroheliograph gave it the playful name *cucumberograph*. [2]

[2] Interestingly, the S082A spectroheliograph with a normal incidence grating in the Wadsworth mount, which operated on the Skylab space station in 1973–1974, received the humorous nickname *overlapper*. The reason was the fact that images of the solar disk in lines differing by less than 26 Å partially overlapped each other.

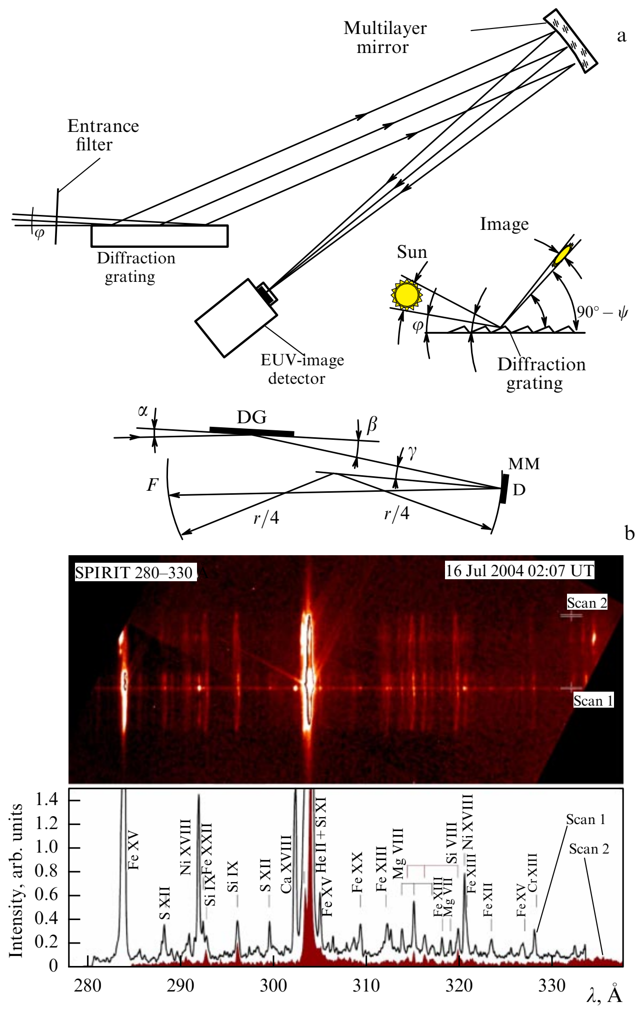

Figure 5. (a) Elements of SPIRIT slitless spectroheliograph aboard the CORONAS-F satellite [26] and its schematic representation with a focusing normal-incidence multilayer mirror and a plane grazing-incidence diffraction grating. (b) Spectroheliogram in range of 280 – 330 Å (July 16, 2004) [26]. Top: spectral-line solar images compressed in dispersion direction in internal diffraction order due to 'angular demagnification' of grating in that direction. Bottom: spectral lineouts obtained at a level including flare region (scan 1, flare class X1.3) and in region of the quiet Sun (scan 2).

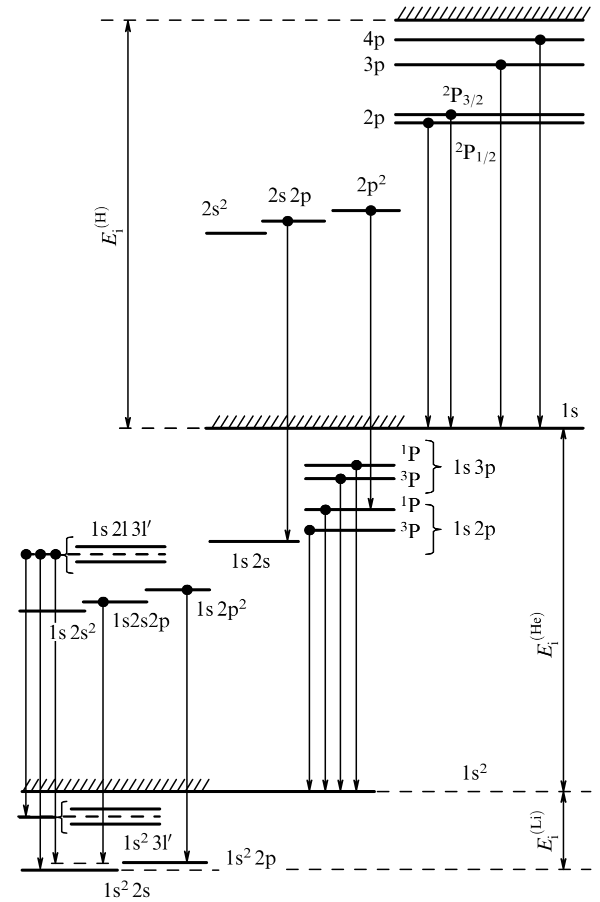

Figure 6. Diagram of H-, He-, and Li-like ion levels, between which the most intense transitions are observed [29].

4. V A Boiko's group's work

Laser plasma was repeatedly used at LPI in research on X-ray and VUV spectroscopy, and later in research on X-ray optics. In the 1970s, the Laboratory of Quantum Radiophysics studied the X-ray and VUV spectra of multiply charged ions excited by high-power pulses of laser radiation. ISAN staff member E V Aglitsky in those years was seconded to LPI and participated in a number of pioneering studies. Mention should be made of the work by E V Aglitsky, V A Boiko, S M Zakharov, and G V Sklizkov reporting the observation of Stark broadening of the lines 520.6 Å (4 → 3 transition) and 3434 Å (8 → 7) in the CVI ion, which made it possible to estimate the course of N_e at distances of 0.1–0.25 mm from the target using the 520.6-Å line and at distances of 0.8–1.4 mm using the 3434-Å line [27]. To observe this effect, laser plasma was imaged onto the slit of a DFS-29 normal incidence spectrograph using an iridium-coated mirror. Using a crystal spectrograph, a spectrogram was recorded that contained about 40 lines of highly ionized iron in the range of 10–18 Å [28].

In the early 1970s, S A Pikuz and A Ya Faenov joined V A Boiko's group (Laboratory of Quantum Radiophysics). In Ref. [29], spectra of H- and He-like ions Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, and V were obtained in the range of 2–18 Å, as were dielectronic satellites of the resonance lines of H- and He-like ions arising from npn′l′–1sn′l′ and $1s2pnl - 1s^2nl$ transitions (Fig. 6). A total of 180 spectral lines were measured, and the wavelength measurement accuracy was 0.002 Å in the region $\lambda \sim 10$ Å and 0.0005 Å for $\lambda \sim 2.5$ Å. The laser pulse energy was ~ 50 J with a duration at half maximum of ~ 1.8 ns and a divergence within 3×10^{-4} rad. A slitless spectrograph with a convex mica crystal was used, which made it possible to obtain panoramic spectra in the range of 0.5 – 19 Å (Fig. 7). NaCl, Mg, Al, SiO_2, P, S, KCl, CaO, Ti, and V were used as targets.

The fruitful work of the group, the core of which was V A Boiko, S A Pikuz, and A Ya Faenov, continued for a number of years. Here are just some of the papers by this scientific group. $2p^5 - 2p^4 3d$ transitions in $[F]_{Y,Mo}$ ions were obtained in laser plasma and identified, i.e. in fluorine-like ions YXXXI and MoXXXIV in the wavelength regions of about 5.4 Å and 4.5 Å, respectively [30]. It was possible to observe satellites of the $1s^2\ {}^1S_0 - 1s3p\ {}^1P_1$ (Ly_β) transition in He-like ions of the elements Mg, Al, Si, P, S, Cl, and K [31]. Efforts were made to measure the electron density N_e from the Stark broadening of the Lyman series transitions of H-like ions, from the intensity ratio of the of the resonance and intercombination lines of an He-like ion, and by the intensity ratios of other spectral lines [32].

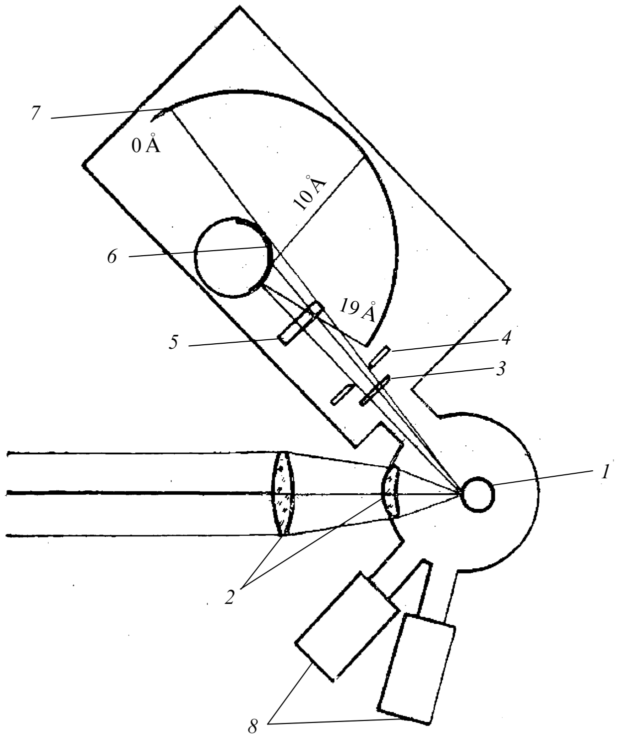

Figure 7. Diagram of experimental setup: *1* — target; *2* — two-component lens ($f = 7.5$ cm); *3* — filter (5-μm lavsan, 0.1-μm aluminum); *4* — limiting aperture stop; *5* — slit for separating tracks when photographing several spectra; *6* — mica crystal; *7* — photographic film; *8* — channels for recording continuous X-ray radiation [29].

5. X-ray and vacuum ultraviolet spectroscopy of laser plasma in I I Sobelman's departments

At that time, work on the spectroscopy of multiply charged ions in laser plasma was also carried out in I I Sobelman's sector of the Laboratory of Quantum Radiophysics, most of whose staff members later, in 1984, moved to the Laboratory of Spectroscopy together with I I Sobelman. Worthy of mention is the trusting relationship and atmosphere of mutual assistance among I I Sobelman's staff members. I would especially like to emphasize the role of I L Beigman, A V Vinogradov, B Ya Zeldovich, and E A Yukov, who would kindly advise experimenters on theoretical issues.

To record the spectra of multiply charged ions, including spectra with spatial resolution, V A Chirkov used a focusing spectrograph with a high light-grasp according to Johann's system (Fig. 8) [33]. The special feature of this system is that the recorded range of the spectrum depends on the position of the source relative to the Rowland circle, the widths of the lines depend to a much smaller extent on the size of the source, and the high aperture makes it possible to record the X-ray spectrum for a very moderate irradiation intensity/energy.

The spectra of multiply charged ions have been used more than once for spectroscopic plasma diagnostics. Using line intensity ratios sensitive to density, temperature, and ionic composition in an optically thin plasma, these characteristics can be determined/estimated. The Stark broadening of spectral lines, in particular the optically thin lines of the Balmer and Paschen series, provides reliable density measurements. Doppler line broadening characterizes the macroscopic motion of the plasma (in most observed regions of laser plasma, the 'expansion-related' Doppler broadening

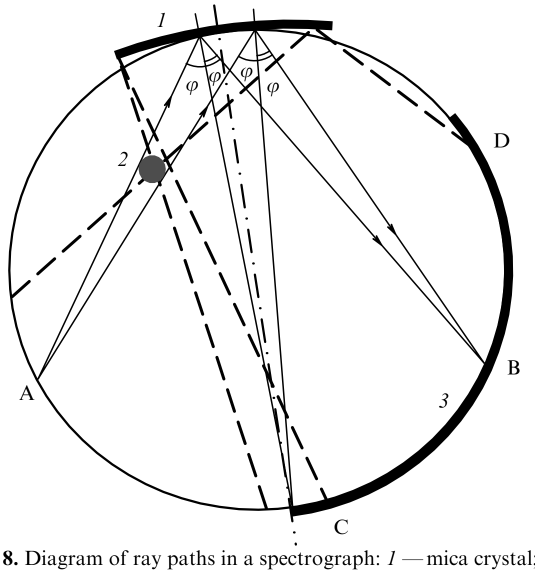

Figure 8. Diagram of ray paths in a spectrograph: *1* — mica crystal; *2* — laser plasma; *3* — photographic film; rays whose extensions converge at point A are focused at point B on photographic film; CD is area of film on which the spectrum is photographed [33].

predominates over the thermal one). Using a domestic grazing incidence spectrograph ($R = 1$ m, $\alpha = 8°$), E N Ragozin obtained spectra of multiply charged ions in the region $\lambda < 300$ Å in order to determine the plasma parameters. Specifically, from the intensity ratios of the transitions $(2p^6 \rightarrow 2s2p^5)/(2s2p^5 \rightarrow 2s^22p^4)$ in O-like ions and $(2p^5 \rightarrow 2s2p^4)/(2s2p^4 \rightarrow 2s^22p^3)$ in N-like ions, one can estimate the electron density [34, 35] (Fig. 9). Based on the Stark broadening of the Balmer series transitions H_α, H_β, and H_γ of the hydrogen-like ion CVI, the averaged electron density was determined [36] (Fig. 10). The slitless version of the DFS-6 spectrograph was used to obtain dispersed spectral images of laser plasma, which made it possible to determine the size of the region of emission/existence of an ion of a particular charge state, as well as the expansion angle [37]. The plasma velocity was estimated from the 'expansion-related' Doppler broadening (Fig. 11). Experiments have shown that N_e at the (adiabatic) Jouguet point is one sixth or less than the critical density of $\sim 10^{21}$ cm^{-3} for neodymium laser radiation. From this, as well as from a set of other data, it followed that a rarefaction jump takes place on the

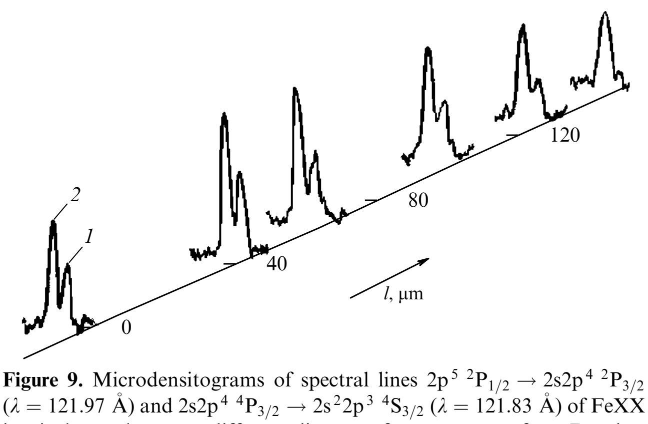

Figure 9. Microdensitograms of spectral lines $2p^5\ ^2P_{1/2} \rightarrow 2s2p^4\ ^2P_{3/2}$ ($\lambda = 121.97$ Å) and $2s2p^4\ ^4P_{3/2} \rightarrow 2s^22p^3\ ^4S_{3/2}$ ($\lambda = 121.83$ Å) of FeXX ion in laser plasma at different distances from target surface. Density-sensitive transition $2p^5 \rightarrow 2s2p^4$ (*1*) weakens significantly faster with distance from target than the transition $2s2p^4 \rightarrow 2s^22p^3$ (*2*) [35].

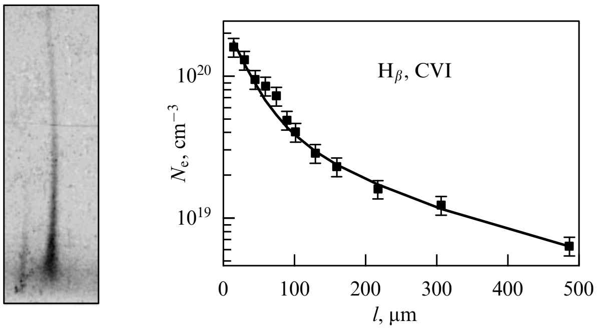

Figure 10. H$_\beta$(λ = 135 Å) of CVI ion in laser plasma. Stark broadening depends on distance to carbon target. On right is profile of N_e determined from broadening of Balmer lines [36].

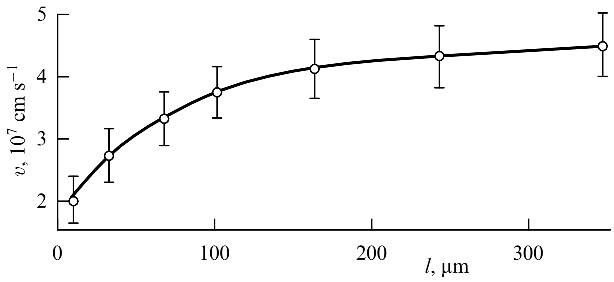

Figure 11. Dependence of plasma velocity in a calcium plume on distance to target determined from Doppler broadening of transitions of CaXIII ion at $q_L \sim 10^{13}$ W cm^{-2} [38].

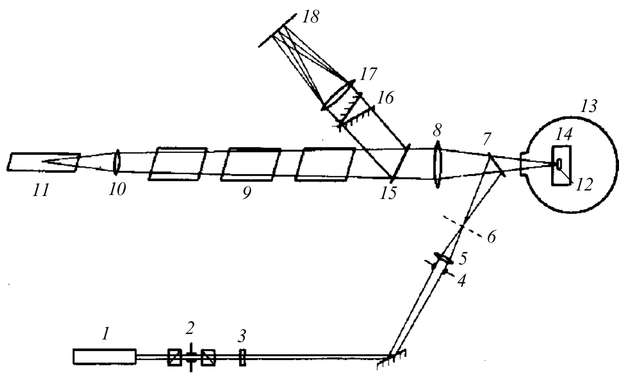

Figure 12. Setup diagram: *1* — master oscillator; *2* — electro-optical shutter; *3* — negative lens; *4* — aperture stop; *5* — injection lens; *6* — focal plane of lens *5*, conjugate with surface of target *12*; *7*, *15* — beam splitters; *8*, *17* — identical lenses; *9* — three amplification stages ∅ 45 mm; *10* — lens; *11* — cell with CCl_4; *13* — vacuum chamber; *14* — X-ray spectrograph; *16* — mirror wedge; *18* — focal plane of lens *17* [41].

critical surface [38, 39]. This effect is underlain by the fact that the limiting electron thermal conduction flux is approximately one and a half orders of magnitude lower than the so-called free-streaming (free-molecular) heat flux and is not capable of providing transonic flow in a supercritical plasma. This conclusion applies to intensities lower than 10^{14} W cm^{-2}.

In addition to the traditional 'master oscillator + amplifiers' laser setup, one with wavefront reversal during SBS with compensation for aberrations of optical elements was used (Fig. 12). It was experimentally shown that in this case the diameter of the region of existence of high charge-state ions is narrower, and the energy density in the focal spot is higher [40, 41]. In this experimental setup, X-ray spectra of multiply charged magnesium and iron ions were obtained with spatial

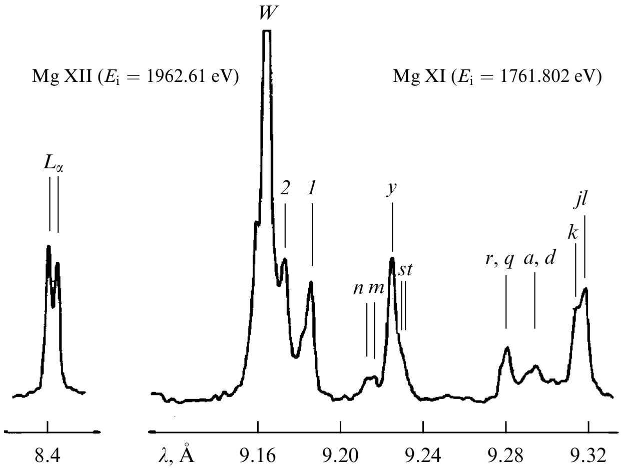

Figure 13. Portion of magnesium spectrogram in the second order of reflection from crystal. *W* and *y* — resonance and intercombination lines of MgXI ions; *m*, *n*, *s*, *t*, *r*, *q*, *a*, *d*, *k*, *j*, *l*, *1*, and *2* — satellites of the resonance line of the MgXI ion, arising from autoionization levels of MgX ion; Lα is resonance doublet of MgXII ion [41].

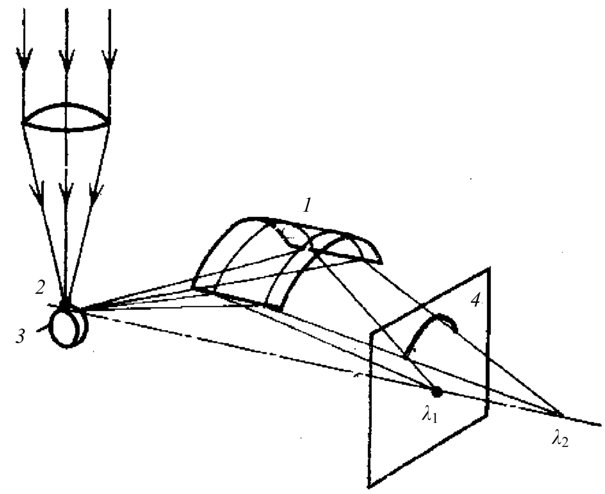

Figure 14. Diagram of an X-ray von Hamos spectrograph ($\lambda_1 > \lambda_2$): *1* — mica crystal; *2* — laser plasma; *3* — target; *4* — plane of photographic film [42].

resolution in the direction normal to the target using a Johann spectrograph with a mica crystal [33]. Figure 13 shows portions of the magnesium spectrogram indicating the spectral lines. The observed intensity ratio of the components of the fine structure of the resonance line of the MgXII ion indicates a smaller optical thickness of the plasma in these spectral lines than is usually observed when focusing with a lens. This fact is also an indication of the small transverse size of the laser plasma.

Using a nanosecond neodymium-glass laser with an energy of ~ 10 J to record the spectra of laser plasma, A P Shevelko used a high-aperture von Hamos focusing spectrograph with a mica crystal (Figs 14–17) [42, 43]. The plasma was located on the axis of the cylinder, and the detector plane could be located either perpendicular to the axis of the spectrograph or on its axis. In the latter case, the 'luminosity' of the von Hamos spectrograph is maximum. With this detector arrangement, the size of the spectral image usually coincides with the size of the source, which distinguishes this setup from the Johann one. The radiation detector was X-ray photographic film, and later a CCD

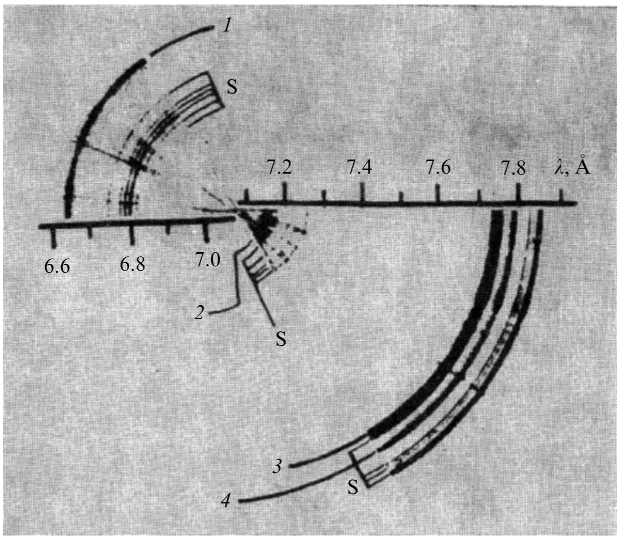

Figure 15. Emission spectrum of aluminum laser plasma in region of 6.5–8.0 Å ($E_L = 5$ J): *1* — AlXII ($1s^2\,^1S_0 - 1s3p\,^1P_1$); *2* — AlXIII ($1s\,^2S_{1/2}$–$2p\,^2P_{3/2,1/2}$); *3* — AlXII ($1s^2\,^1S_0$–$1s2p\,^1P_1$); *4* — AlXII ($1s^2\,^1S_0$–$1s2p\,^3P_1$); S — satellites [42].

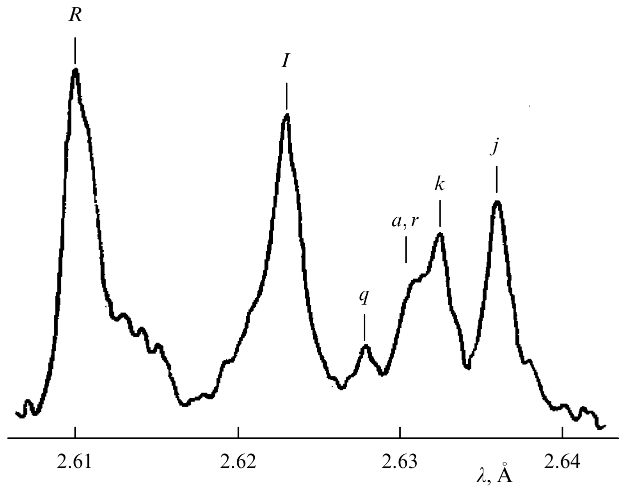

Figure 16. Densitogram of emission spectrum of TiXXI ions in laser plasma ($E_L = 25$ J): R — $1s^2\,^1S_0 - 1s2p\,^1P_1$; I — $1s^2\,^1S_0 - 1s2p\,^3P_1$; j — $1s^2 2p\,^2P_{3/2} - 1s2p^2\,^2D_{5/2}$; q — $1s^2 2s\,^2S_{1/2} - 2s2p(^3P)1s\,^2P_{3/2}$ [42].

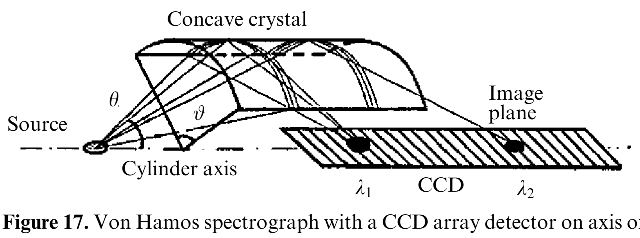

Figure 17. Von Hamos spectrograph with a CCD array detector on axis of the cylinder [44].

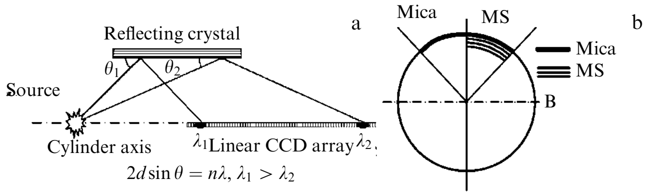

Figure 18. Schematic of von Hamos X-ray focusing spectrometer in a plane passing through axis of the spectrometer (a), and geometry of relative measurements of reflectance of a mica crystal and a multilayer structure (MS) deposited on inner surface of mica (B is position of focal plane) (b) [45].

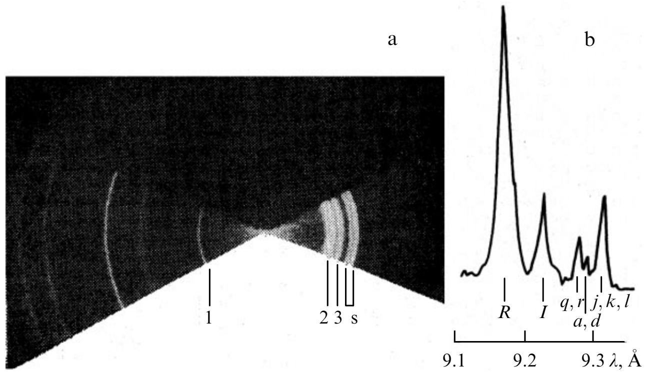

Figure 19. (a) Emission spectrum of MgXII, MgXI, and MgX ions in region of 7.4–9.5 Å and (b) densitogram of emission spectrum of MgXI and MgX ions [46].

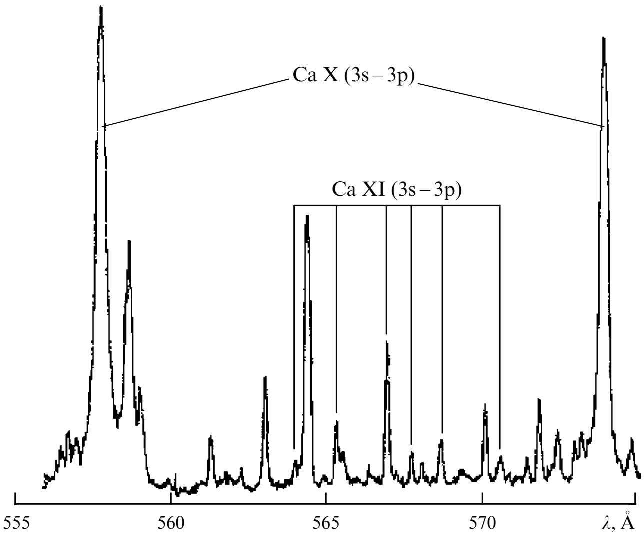

Figure 20. Part of spectrum of a calcium target near resonance lines of Na-like ion CaX, with indications of lines of Ne-like ion CaXI [52].

array [44]. Interestingly, along with a natural crystal, the spectrograph can use a multilayer structure (MS), in particular the W/B_4C structure with a period of 12 Å deposited on the surface of the crystal [45] (Fig. 18).

In joint work between the Laboratory of Spectroscopy and the Laboratory of Luminescence, a study was made of the spectrum of magnesium plasma excited by pulses of a picosecond ruby laser [46]. The laser consisted of a self-mode-locked oscillator and an amplifier operating at a low (100 K) temperature. This made it possible to obtain a short train consisting of 1–3 pulses with a duration of 10–20 ps and an energy of up to 0.5 J. A von Hamos spectrograph was used, with the X-ray photographic film oriented perpendicular to its axis. In one or two laser shots, the resonance and intercombination lines of the He-like magnesium ion and its satellites, as well as the resonance line of the H-like ion, were recorded (Figs 19, 20). As the number of shots increased, $1s^2 - 1snp(n = 3-8)$ lines of the He-like ion were observed. It is noted that the electron temperature, estimated at 700 eV from considerations of the kinetics of H-like ion production, turned out to be significantly higher than T_e, determined from the ratio of the intensity of the resonance line of the He-like ion to the intensity of satellites *j*, *k*, *l*, excited as a result of dielectronic recombination.

5.1 Spectroscopy of 3–3 transitions of Ne-like ions

In the mid-1970s, A N Zherikhin, K N Koshelev, V S Letokhov (ISAN) and A V Vinogradov, I I Sobelman, E A Yukov (LPI) formulated an approach to the production of lasers in the far VUV (soft X-ray) region of the spectrum based on transitions in multiply charged Ne-like ions in plasma [47, 48]. In the former work, it was proposed to produce a population inversion during rapid (picosecond) heating of a pre-produced plasma (two-stage plasma heating). In the latter, it was shown that a significant inversion also occurs in a quasi-stationary mode. Both approaches turned out to be in demand and formed the basis for all successful work on the demonstration of lasing based on transitions of multiply charged ions in the soft X-ray region of the spectrum, the first of which should be considered the work of the Livermore Laboratory [49].

At that time, transitions between levels of the $2p^53l$ configurations of Ne-like ions were partially studied only for the first members of the neon isoelectronic sequence. Specifically, owing to the work of H P Garnir et al. [50] in 1978, the wavelengths and energy levels for the SVII ion became partially known: 16 lines in the range of 600–1500 Å were identified, and energy values were assigned to twenty-two of the 26 energy levels of the $2p^53s$, $2p^53p$, and $2p^53d$ configurations. Most of these lines were observed in beam–foil experiments with insufficiently high spectral resolution.

To obtain and record the spectra of the S VII ion at the LPI, a laser plasma and a DFS-29 normal incidence spectrograph were used. In collaboration with ISAN staff members E Ya Kononov, A E Kramida, and L I Podobedova, 23 new lines were identified [51]; in four cases, the classification of lines assigned by H Garnir was changed, and the wavelength measurement accuracy was improved by an order of magnitude. Four energy levels out of 26 were found for the first time; 10 energy levels were refined by 100–1500 cm^{-1}, and the energies of six more levels were refined by 20–40 cm^{-1}.

Subsequently, the spectra arising from transitions between the levels of the $2p^53s$, $2p^53p$ and $2p^53d$ configurations in Ne-like ClVIII, KX, and CaXI ions were studied [52, 53]. In the identification of the spectrum of CaXI, an important role was played by an excellent spectrogram obtained at ISAN on a normal-incidence vacuum spectrograph with a grating of 1200 mm^{-1} with $R = 6.65$ m (see Fig. 20). In total, more than 130 lines were classified in the laser plasma spectra.

While moving along the isoelectronic sequence of Ne I, an effective technique was used to predict the wavelengths of 3–3 transitions. It relies on theoretical calculations of energy levels and involves extrapolating or interpolating the reduced difference between the theoretical and experimental transition energies. Perturbation theory calculations with expansion in powers of $1/Z$, published in Refs [54, 55], were used as theoretical values.

6. X-pinch

S A Pikuz, already a staff member of the Department of High Energy Density Physics, proposed and implemented a configuration in a high-current (> 100 kA) pulsed vacuum diode, which received the name *X-pinch* [56, 57] (Fig. 21). It consists of two (or several) thin wires intersecting at one point. A remarkable feature of the X-pinch is that plasma implosion (pinching) occurs at a fixed point, at the intersection of the wires, which allows diagnostics with high spatial and temporal resolution. Essentially, an X-pinch is a nanosecond point source of high-brightness X-ray and VUV radiation, whose spectral composition depends on the wire material. According to the authors' estimates, a density $N_e \sim 10^{22}$ cm^{-3} is achieved in the pinch.

The X-pinch concept gave rise to a series of studies on its characteristics and the specific spectra of multiply charged ions excited in it. Some of the work was carried out jointly with staff members of VNIIFTRI, Cornell University, laboratories in Livermore and Los Alamos, and others [57–61]. For instance, in Ref. [57], the spectra of Na- and Mg-like molybdenum ions MoXXXII and MoXXXI were obtained and studied in the range of 4.4–5.0 Å. Satellites of resonance lines of the Ne-like Mo XXXIII ion were identified, which were excited in the electron capture to the autoionization energy levels $2l^73l'3l''$ of the MoXXXII ion and $2l^73l'3l''3l'''$ levels of the MoXXXI ion. In Ref. [58], experiments with an aluminum wire were carried out at Cornell University, and satellites of the resonance line of the He-like ion were observed in Li-, Be-, B-, and C-like aluminum ions. In Ref. [59], in laser plasma and in X-pinch plasma it was possible to observe lines corresponding to $1s^2\,{}^1S_0 - 1snp\,{}^1P_1$ $(n = 6-12)$ transitions in the He-like AlXII ion (Fig. 22). Precision measurements of the wavelengths of the Rydberg lines made it possible to determine the energy of the ground state of the ion with a relative accuracy of $\sim 5 \times 10^{-5}$ (2085.98 ± 0.10 eV).

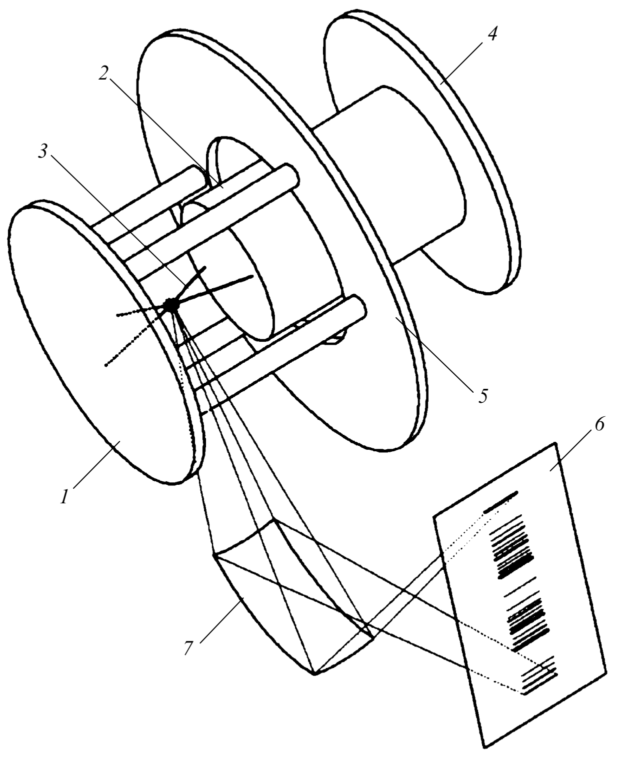

Figure 21. Experimental configuration (X-pinch): *1* — anode; *2* — cathode; *3* — molybdenum wires; *4* — high-voltage electrode; *5* — grounded electrode; *6* — X-ray photographic film; *7* — spherically curved mica crystal [57].

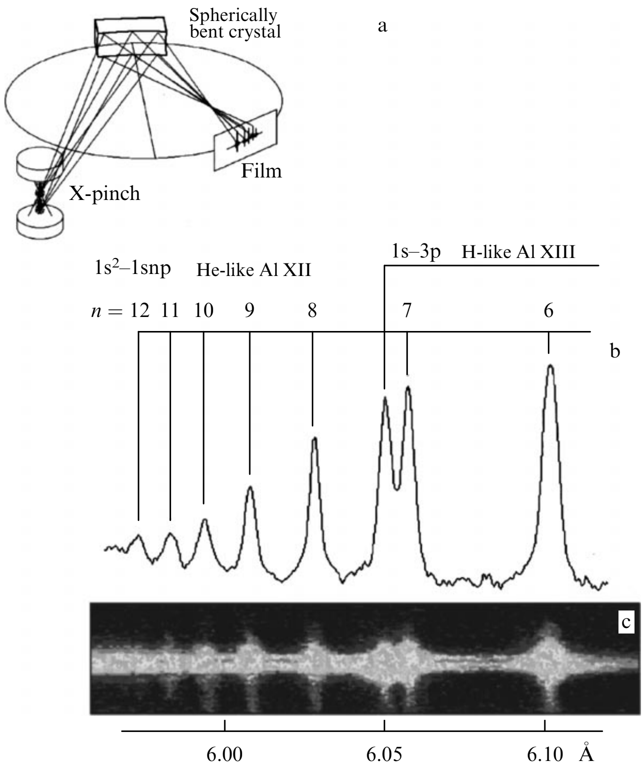

Figure 22. (a) Experimental configuration (X-pinch); (b) spectrum of aluminum plasma recorded using a spherical crystal spectrometer with one-dimensional spatial resolution with a mica crystal [59]; (c) — section of spectrogram.

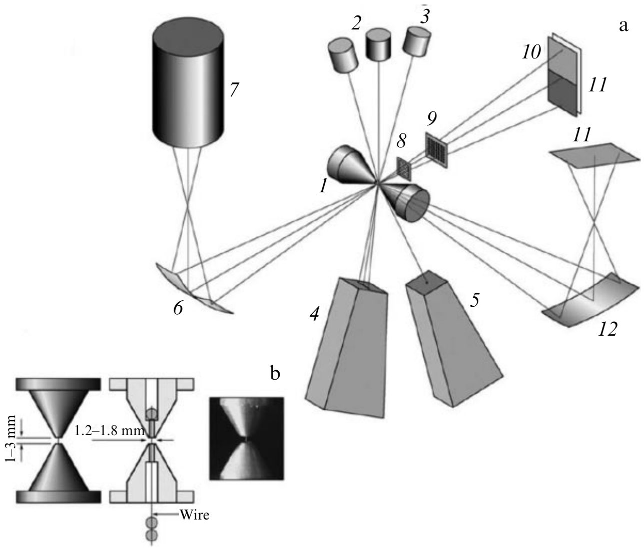

Figure 23. (a) Recording of radiation from a hybrid X-pinch: *1* — hybrid X-pinch; *2* — photodiodes; *3* — X-ray diffraction detector; *4* — time-integrated slit camera; *5* — time-integrated pinhole camera; *6* — crystal; *7* — streak camera; *8, 9* — depicted objects; *10* — filters; *11* — image plates; *12* — spherically bent spectrograph crystal. (b) Hybrid X-pinch with conical electrodes and its cross-sectional image [61].

Subsequently, studies were carried out on a pinch with one wire connecting two conical electrodes (Fig. 23). This configuration came to be known as a hybrid X-pinch [61]. In many of its characteristics, the hybrid X-pinch is not inferior to the standard X-pinch, but is much simpler to operate.

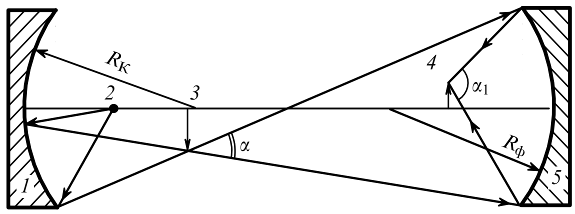

Figure 24. Simplest scheme of projection X-ray lithography. *1* — spherical multilayer mirror-condenser; *2* — X-ray source; *3* — photomask; *4* — X-ray resist; *5* — spherical focusing multilayer mirror [64].

7. Soft X-ray optics

Thanks to the development of high technologies, the last quarter of the 20th century saw the development of new X-ray optical elements. We are dealing Fresnel lenses, aspherical mirror optics, multilayer X-ray mirrors, transmitting diffraction gratings with a high line frequency, reflection gratings with a spacing that varies across the aperture according to a given law, and other elements. Their appearance significantly expanded the possibilities of experimentation in the vacuum region of the spectrum and led to changes that are rightly called a revolution in X-ray optics. The pioneer in this field at LPI was A V Vinogradov, who published a theoretical paper together with B Ya Zeldovich [62]. A V Vinogradov managed to interest a group at the Kharkov Polytechnic Institute (KhPI), led by A I Fedorenko and V V Kondratenko, where they developed the technology for synthesizing multilayer mirrors. In Russia, research and development of multilayer optics and other X-ray optical elements developed extremely successfully at the Institute for Physics of Microstructures of the Russian Academy of Sciences (Nizhny Novgorod) under the leadership of N N Salashchenko. E N Ragozin's group collaborated with both teams as long as it was possible.

In the second half of the 1980s, A V Vinogradov, together with N N Zorev, came up with a pioneering idea to use X-ray radiation for projection microlithography using specular X-ray optics, including normal-incidence multilayer mirrors [63, 64]. It was stated that "...the use of X-ray optics elements, the production of which is fully supported by the current level of technology, makes it possible to ensure the production of microstructures with element sizes of the order of tens of nanometers..." [64]. This topic is closely related to vacuum spectroscopy and is largely based on its achievements.

As is well known, laser plasma can be a source of both predominantly line radiation and quasi-continuous radiation when we are talking about a target with a sufficiently high atomic number. This circumstance was used to determine the resonance reflection profile of multilayer mirrors (MMs). Such work began in the early 1990s in the Department of Spectroscopy for space research, together with the team led by I A Zhitnik. For this purpose, a spectrograph design with a transmission grating and a focusing normal incidence MM was used [65] (Figs 25, 26). Subsequently, this setup was repeatedly used to estimate MMs and their homogeneity over the aperture (see, for example, Refs [66–68]).

The quality of the image produced by a focusing normal incidence MM was also estimated, and sub-arcsecond angular resolution at a wavelength of 17.5 nm was experimentally demonstrated (Fig. 27) [69, 70].

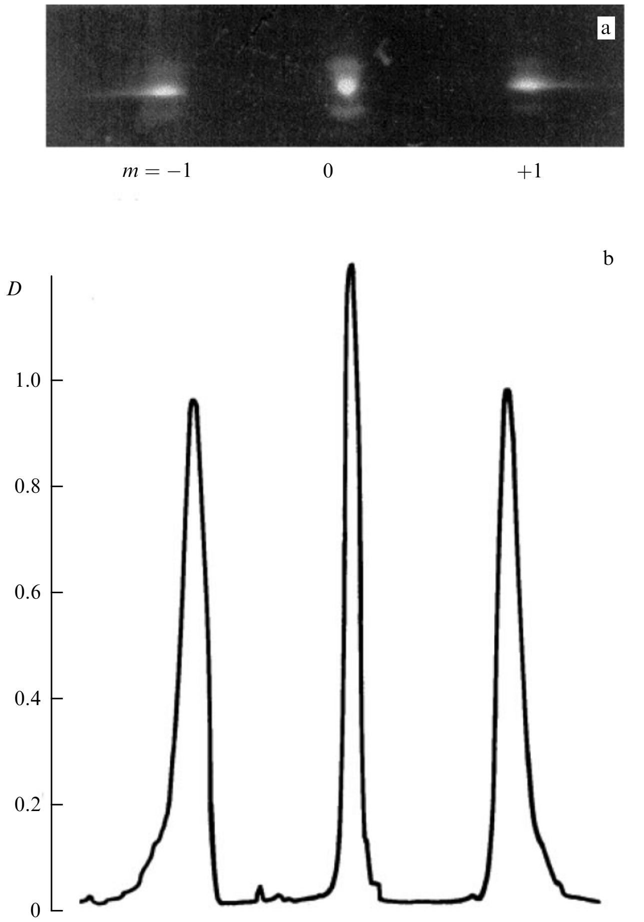

Figure 25. Spectral reflectivity profile of concave Mo/Si multilayer mirrors ($\lambda_0 = 19.5$ nm, $\Delta\lambda_{1/2} = 2.1$ nm) determined using a laser-plasma radiation source in a spectrograph configuration with a free-standing transmission diffraction grating [65].

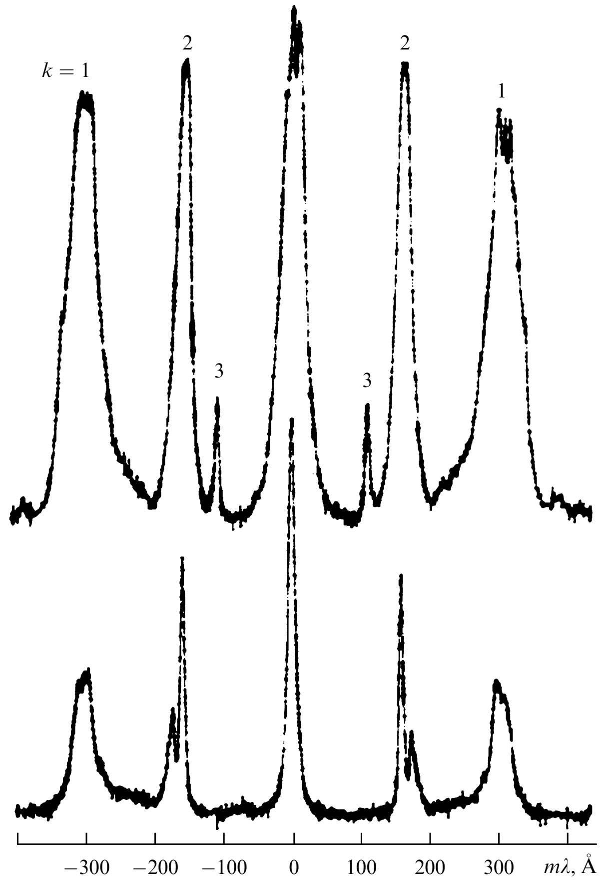

Figure 26. Panoramic microdensitogram of spectrum reflected from a concave Mo/Si multilayer mirror with maximum of first interference reflection order at a wavelength of 306 Å. Top: Directly from mirror; bottom: using an aluminum filter with a thickness of 0.2 microns. Numbers at maxima indicate interference order of reflection [67].

The reflection coefficient of a periodic binary MM A/B peaks at wavelength λ_0, satisfying the Bragg–Wolf condition $m\lambda_0 \simeq 2dn\cos\theta$, where d is the period of the multilayer structure, i.e., the sum of the thicknesses of layers of materials A and B in a period, n is the average value of the refractive index over the period, θ is the angle of incidence of the radiation, measured from the normal, and m is the order of interference. Typically, the relative width (FWHM) of the resonant reflectivity profile is $\delta\lambda_{1/2}/\lambda \sim 0.1-0.01$. Therefore, the spectral selectivity (resolution) of such a mirror is in the range of 10–100, this being so under the condition of cutting off radiation in the wings of the reflection profile and in other interference maxima. Using focusing MMs together with a free-standing transmitting grating, it is possible to achieve a resolution of 200–300, which is usually limited by the regularity of the grating lines. Finally, when using focusing MMs together with a plane reflection grating, a resolution of 10^3-10^4 or higher is achieved, including in a stigmatic spectrograph [71–73].

In many cases, it is necessary to obtain a spectrum over a relatively broad range, and not within the resonant profile of the MM reflection. This is achieved in a panoramic spectrograph with a grazing incidence toroidal mirror and a free-standing transmission grating (Figs 28, 29) [74].

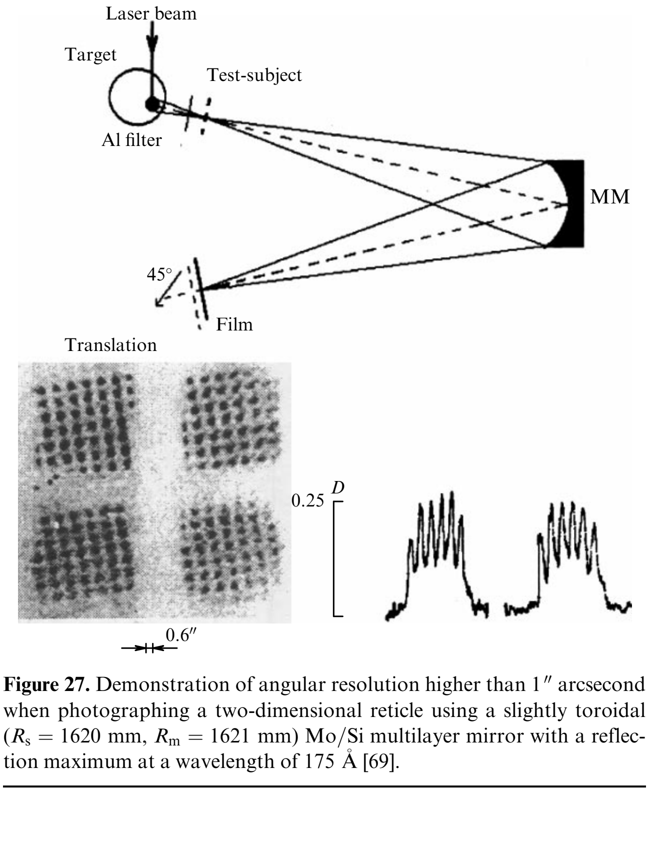

Figure 27. Demonstration of angular resolution higher than 1″ arcsecond when photographing a two-dimensional reticle using a slightly toroidal ($R_s = 1620$ mm, $R_m = 1621$ mm) Mo/Si multilayer mirror with a reflection maximum at a wavelength of 175 Å [69].

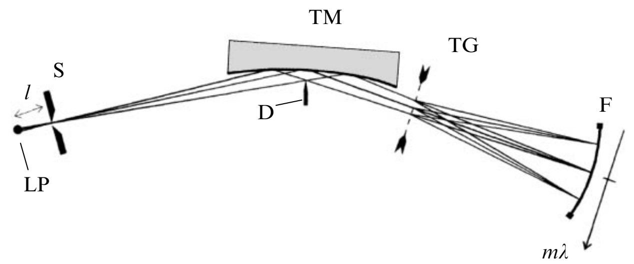

Figure 28. Schematic of a panoramic quasistigmatic spectrograph for the soft X-ray range: LP — laser plasma; S — entrance slit; TM — grazing incidence toroidal mirror; D — aperture stop; TG — freestanding transmission grating; F — X-ray photographic film; l is LP–S distance consistent with grazing incidence angle and mirror radii to achieve stigmatism [74].

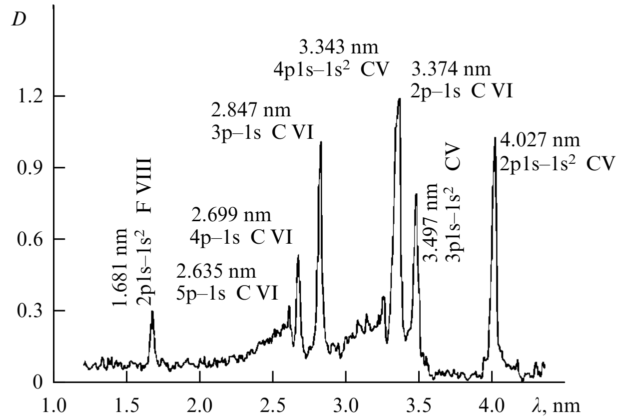

Figure 29. Short-wavelength part of spectrogram of a Teflon target recorded using setup shown in Fig. 28 (grazing angle: 4°; transmission grating line density: 5000 mm^{-1}). Spectrum was excited by laser pulses: 0.1 J, 5 ns, 0.54 μm [74].

7.1 Broadband multilayer mirrors based on aperiodic multilayer structures

A periodic MM realizes the maximum reflection coefficient at a fixed wavelength that satisfies the Bragg–Wolf condition. An aperiodic multilayer structure can satisfy other criteria. Obviously useful criteria include, for example: (1) the maximum integral reflectivity over a given range of wavelengths or angles of incidence; (2) the same, but taking into account the source function; (3) the reflection of attosecond radiation pulses while maintaining their shape/duration; (4) the maximum uniform reflection coefficient over a given wavelength range [75–78]. The last criterion is especially useful when designing a broadband spectrograph. The multilayer structure is found by numerically solving the inverse problem of multilayer optics.

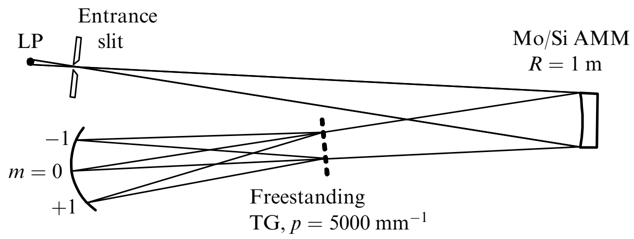

Figure 31. Stigmatic broadband spectrograph with an aperiodic Mo/Si multilayer mirror. Coating was applied in laboratory of Prof. V V Kondratenko (Kharkov Polytechnic Institute) [78–80].

The first aperiodic Mo/Si structure was designed for maximum uniform reflectivity in the range of 125–250 Å at nearly normal incidence ($\theta = 5°$), and broadband multilayer mirrors were deposited on concave substrates in the laboratory of V V Kondratenko at the KhPI (Fig. 30) [79, 80]. Subsequently, they were repeatedly used in physical experiments in the configuration of a stigmatic spectrograph (Fig. 31) with a free-standing transmission grating to record the spectrum of a laser-plasma radiation source with a pulsed xenon jet (Fig. 32) [81]; to record line radiation arising from the charge exchange of BV and CVI ions with the atoms of a noble gas jet (He, Ne, Xe) [82]; to record soft X-ray radiation generated when a femtosecond IR laser is reflected from a counterpropagating relativistic plasma wave of electron density [83]; and others.

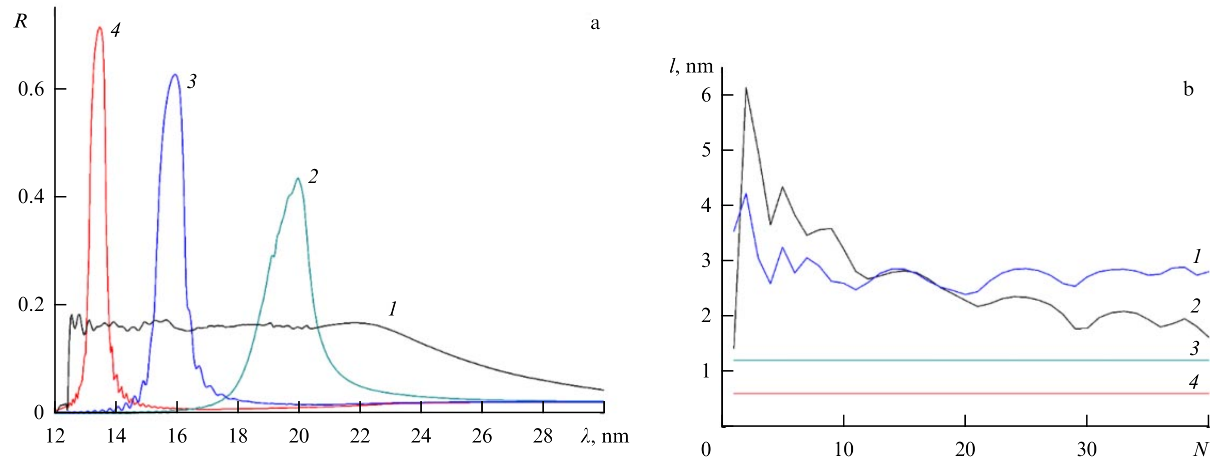

Figure 30. (a) Calculated reflectance of an aperiodic MM at normal incidence in region of 12–30 nm (curve *1*). Shown for comparison are reflection coefficients of periodic MMs, with reflection maxima at wavelengths of 20 (*2*), 16 (*3*), and 13.5 nm (*4*). (b) Thicknesses of Mo (*1*), Si (*2*), Mo-on-Si (*3*), and Si-on-Mo (*4*) transition layers of an aperiodic MM optimized for maximum uniform reflectivity in range of 12.5–25 nm. Layer numbering proceeds depthwise, from surface to substrate [78, 80].

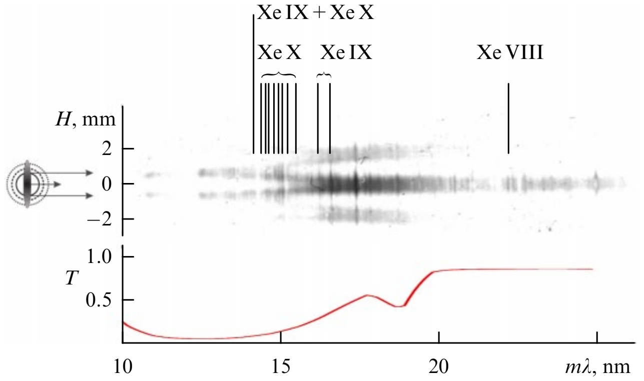

Figure 32. Spatially resolved spectrum of plasma excited in a pulsed Xe jet. Some lines belonging to Xe VIII–Xe X ions are indicated. On left is a symbolic cross-sectional image of Xe jet with spindle-shaped laser plasma. Arrows indicate direction of observation. In plot below: transmission of a conventional 0.5-mm-thick layer of neutral Xe with a density of 2.2×10^{18} cm^{-3}. Radiation from central (in altitude) region of plasma passes through a layer of cold plasma of greatest thickness and experiences strongest absorption, which causes the 'eating out' of central (in altitude) part of spectrum and the 'splitting' of short-wavelength part of spectrum in height [81].

7.2 VLS gratings

In recent years, in the Spectroscopy Department of the LPI a start has been made on the development of spectrometers involving reflection gratings with spacing varying across the aperture according to a given law: so-called VLS gratings (Varied Line-Space gratings) (Fig. 33) [84, 85]. When developing a VLS spectrometer, the specifics of the scientific task, the source, and the radiation detector are taken into account. VLS grating parameters are determined by the spectrometer configuration and their set is tailored for each type of device.

The advent of VLS gratings, along with multilayer mirrors, freestanding transmission gratings, Fresnel zone plates, etc., became part of the renaissance of X-ray optics. Currently, VLS gratings are widely used worldwide in a variety of specialized spectrometers for studying the emission spectra of laser plasma and plasma of fast electrical discharges, astrophysics, synchrotron radiation channels, metrology, reflectometry, X-ray fluorescence analysis and microscopy using synchrotrons, and free electron lasers and other radiation sources, and when analyzing biological objects, etc. An important feature of VLS-grating spectrometers is that the spectrum is produced on a plane surface. This makes them compatible with modern solid-state detectors with an electrical image readout and a flat sensitive surface, in particular 2D-array charge-coupled devices (CCDs).

The combination of a broadband normal-incidence focusing MM and a plane grazing-incidence VLS grating makes up a high-resolution stigmatic spectrograph whose operating range coincides with the spectral reflectance band of the MM. Two versions of such a device were implemented [86–90]: with MMs based on aperiodic structures Mo/Si (125–250 Å) (Figs 34, 35) and Mo/Be (110–140 Å). The Mo/Be structure was synthesized at the Institute for Physics of Microstructures of the Russian Academy of Sciences. Along with spectral resolution, the instrument provides spatial resolution in the direction crossed with respect to the direction of dispersion, and is suitable for diagnosing plasma and other sources of VUV radiation, the resolution being determined by the size of the detector pixels.

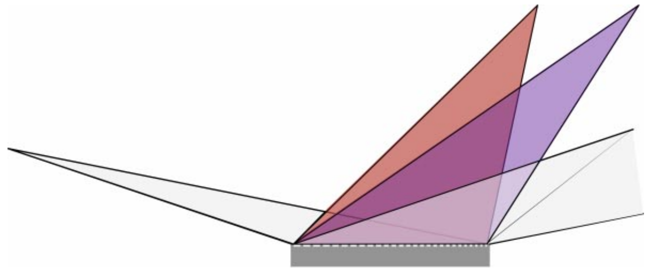

Figure 33. Symbolic representation of operation of a grating with a spacing that varies monotonically across the aperture according to a given law (VLS grating). It is convenient to describe groove frequency by polynomial $p(y) = p_0 + p_1 y + p_2 y^2 + p_3 y^3 + \ldots$ [85].

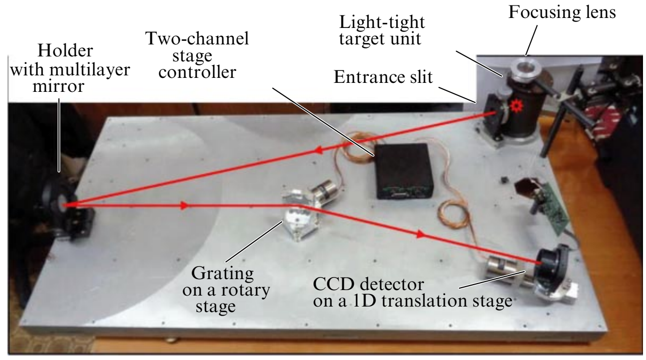

Figure 34. Broadband imaging spectrograph with a resolution of 26 μm (Mo/Si: 12.5–30 nm, Mo/Be: 11–14 nm; $\lambda/\delta\lambda \sim 1000$). Mo/Be mirror was synthesized at IPM RAS [86–90].

Based on spherical grazing incidence VLS gratings, flat-field spectrographs in the range of 50–275 and 25–140 Å, compatible with modern CCD detectors, were implemented (Fig. 36) [89, 91]. As with the stigmatic spectrograph, the spectral resolution is determined by the radiation detector and is numerically equal to the product of the plate scale times twice the detector pixel size. Recently, under an agreement with the Institute of Applied Physics of the Russian Academy of Sciences (Nizhny Novgorod), a transportable version of the flat-field spectrograph for both indicated ranges has been made, equipped with two replaceable VLS gratings with $p_0 = 1200$ and 2400 mm^{-1} [92].

A scanning grazing incidence spectrometer/monochromator with a constant deviation angle according to the Hettrick–Underwood scheme was implemented for the region of 5–30 nm, consisting of a spherical mirror and a plane VLS grating [93]. Wavelength scanning is performed by simply rotating the VLS grating, while the focal length remains invariable. An original concept of a single-element high-resolution monochromator with a constant deviation angle with a plane VLS grating was also designed, in which scanning is carried out by translating the VLS grating along its surface [94]. The new approach is suitable for monochromatization of both a nearby source (for example, laser plasma) and a distant one (a source in a synchrotron orbit). Also performed was a comparative analysis of various monochromator designs suitable for measuring the reflection and transmission coefficients of X-ray optical elements in the SXR range [95].

One of the outcomes of the work was the development of the basis of the technology for manufacturing VLS gratings using the interference lithography technique together with

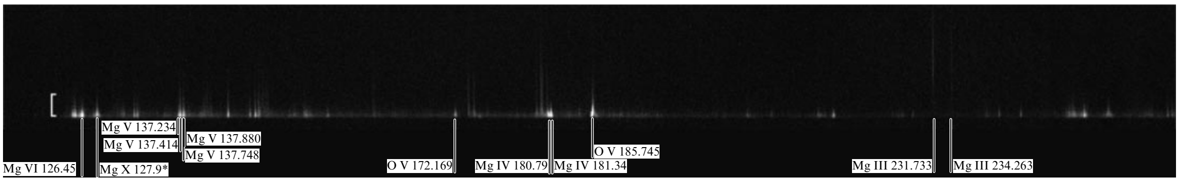

Figure 35. Spectrum of magnesium plasma with spatial resolution in direction normal to target. At right edge of spectrum, a region of 125–128 Å is visible in the second diffraction order. Bracket on left indicates a vertical scale of 0.5 mm [86].

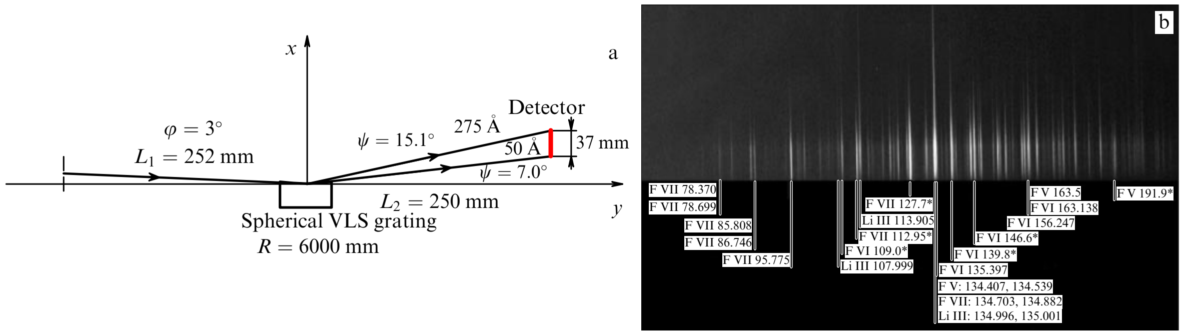

Figure 36. Spectrographs with flat-field in region of 50–275 Å with a grating in which groove frequency varies from 1060 to 1360 mm^{-1}, or in region of 25–140 Å with a grating in which groove frequency varies from 2100 to 2700 mm^{-1} [89, 91, 92].

JSC HoloGrate (St. Petersburg) and Scientific and Production Association GIPO (Kazan). The photolithographic process is preceded by the calculation of the recording configuration that provides the required distribution of interference fringe frequency over the surface of the blank (solving the inverse problem of interference lithography). When recording, radiation with a wavelength of 0.488 μm (HoloGrate) and 0.53 μm (GIPO) was used. Plane VLS gratings with the central groove frequency $p_0 = 600$ mm^{-1} and spherical VLS gratings ($R = 6000$ mm, $p_0 = 1200$ and 2400 mm^{-1}) were manufactured. All gratings were successfully tested in spectrographs when recording line spectra of multiply charged ions in laser plasma.

So, LPI has mastered methods for calculating, optimizing, and designing VLS spectrometers of various types, including analytical calculations and constructing spectral images by the numerical ray tracing technique. The accumulated experience allows us to design specialized VLS spectrometers that take into account the specifics of the scientific task and the source of SXR radiation. Experience has been gained in making 'hardware' samples of VLS spectrometers, including alignment in the visible range and final alignment when recording line spectra of multiply charged ions in plasma. The capabilities of spectrometers for plasma diagnostics were demonstrated.

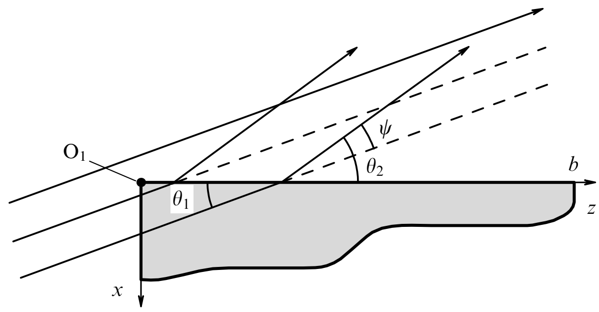

Figure 37. Geometry of the radiation path when the analyzed beam is incident on the base surface of a diamond from the inside [97].

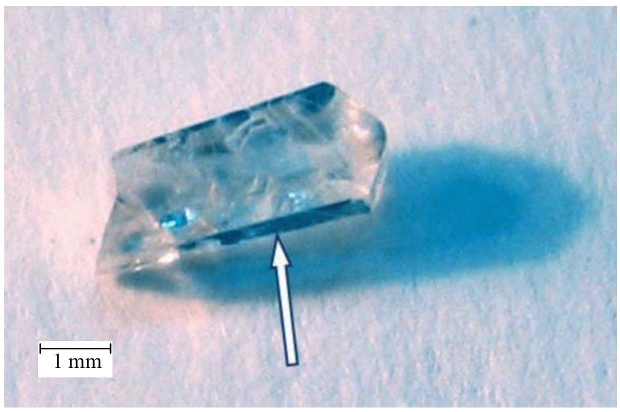

Figure 38. X-ray prism made at LPI from a Yakut diamond. Arrow shows direction of input of primary beam being decomposed into the spectrum. (Photo of prism courtesy of A G Tur'yansky.)

8. X-ray prism spectroscopy

As the wavelength shortens and approaches the hard X-ray range, absorption in materials weakens, and it becomes possible to use refraction to decompose radiation into a spectrum. In the hard X-ray range, longer-wavelength radiation is refracted through a larger angle, in contrast to the visible range. The idea of using a prism as a dispersive X-ray optical element, as far as I know, belongs to A G Tur'yanskii [96–98]. He used a diamond prism (Fig. 37, 38) to decompose into a spectrum the primary polychromatic radiation of a microfocus X-ray tube with a copper anode; to measure the transmission spectra of radiation passed through a sample of bromonaphthalene ($C_{10}H_7Br$) (Fig. 39) and other objects; to study undulator radiation at the ESRF synchrotron; and others [99]. The effectiveness of its use for continuous monitoring of harmonics of an X-ray free electron laser was substantiated (Fig. 40).

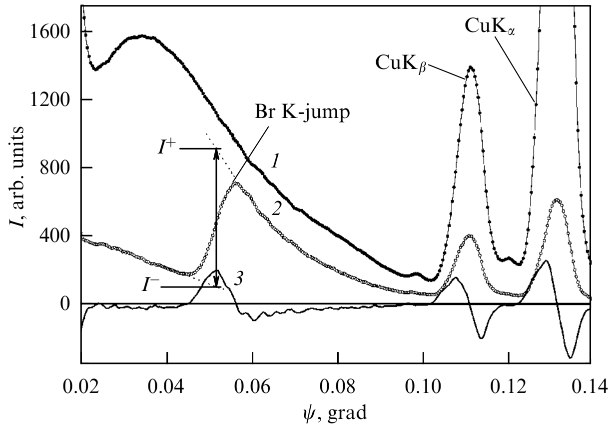

Figure 39. Angular dependences of intensity of refracted radiation $I(\psi)$: *1* — before introduction of a bromonaphthalene ($C_{10}H_7Br$) sample; *2* — after introduction; *3* — derivative $dI/d\psi$ for dependence *2* [98].

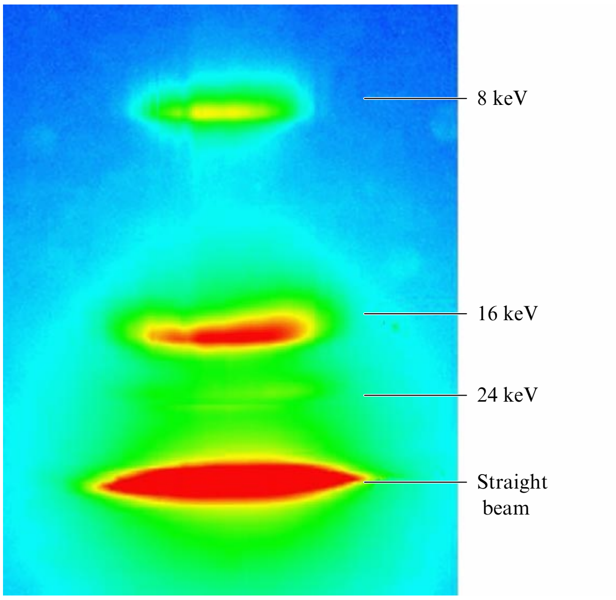

Figure 40. Harmonics of ESRF synchrotron undulator obtained by decomposition into a spectrum with a diamond prism [100].

Critical conditions for decomposition into a spectrum by an X-ray prism are a minimal departure of the refracting facet from planity, surface roughness less than 1 nm, and low attenuation of radiation in the prism material. A prism that meets all these requirements was first manufactured at the Lebedev Physical Institute in the laboratory of A A Gippius in 2000 from a natural single crystal of Yakut diamond (see Fig. 38). Prism refractive spectroscopy is most promising for studying fast pulsed processes [100]. For its effective use in laboratory practice, bright microfocus X-ray sources are required.

The future of refractive spectroscopy in general and its resolving power will be determined by technological capabilities, namely the perfection of the prism surface near its apex.

9. Conclusions

At the first stages of mastering a particular spectral range, spectroscopy as measuring wavelengths and classifying transitions while determining energy levels is an end in itself. After this, it becomes possible to refine the theoretical calculations of the energy levels of multiply charged ions. Of course, this does not rule out the possibility that existing calculations help in classifying experimental spectra. It becomes possible (and tempting) to use spectroscopic data to determine the physical conditions in a plasma. Doppler and Stark broadening of optically thin lines are of undisputable value. The use of spectral line ratios for plasma diagnostics is based on theoretical calculations within the framework of multilevel collisional-radiative models, which must also be correlated with assumptions about physical conditions, such as stationarity or nonstationarity of the ion charge-state distribution or the applicability of the quasi-stationary approximation for the populations of excited states. Finally, spectroscopic techniques are validly used in the development of new X-ray optical elements, instruments and sources in the X-ray and VUV spectral ranges, as well as new production technologies. LPI's research in this area went through all these stages.

Looking back at the past decades, we can note with satisfaction that pioneering proposals and constructive ideas were made at LPI on the topics under discussion, which were subsequently successfully implemented, including in foreign laboratories. Some examples are X-ray lasers based on transitions of multiply charged ions in plasma, methods for diagnosing plasma using line spectra of multiply charged ions, projection X-ray lithography, aperiodic multilayer mirrors and optical-spectral devices based on them, and a number of others.

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