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Final Scientific Report

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Cooperation in Applied Science and Technology Program

"Soft x-ray and extreme ultraviolet optical devices for scientific and industrial applications"

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CONTENTS

	page
I. Abstract	2
II. Specific benefits to American and Russian side from the project	3
III. Main goals of the project	5
IV. New optical short wavelength devices for high sensitivity, high resolution spectroscopic, angular and polarization measurements using multicharged ion beams and hot plasma	6
IV-1. Introduction	-
IV-2. Polarimeter-spectrometer with GCC and MLM for soft x-ray and EUV	8
IV-3. High sensitivity EUV spectrometer with GCC for EUV region	10
IV-4. Application of new optical devices for spectroscopic studies of interaction of multicharged ion beams with gaseous targets in the EUV region	12
V. The potential applications of new optical devices for EBIT and other sources of multicharged ions. The commercial potential of this project	15
VI. Conclusion	17
VII. References	18
VIII. List of publications	21
IX. List of patent applications	22
X. List of conferences	23
XI. The financial report	24

I. ABSTRACT

Construction and testing of prototype new optical devices for the extreme ultraviolet (EUV), soft x-ray (SXR) and x-ray region, including compact spectrometer / polarimeter based on multilayer mirror and glass capillary converter optics.

Development of more complex optical devices for imaging, guiding and focusing of short wavelength radiation for atomic physics and synchrotron radiation applications.

International collaboration between Russian Scientific Technical Organizations, particularly V / O Aviaexport / Aviatechnologies and USA University of Nevada, Reno.

II. Specific benefits to American and Russian side from the project.

1. For both , American host and Russian visitor, scientific information exchange was very important.

2. Prof. R.Bruch learned about new glass capillary optics technology and new plasma diagnostics methods.

3. Prof. V.Kantsyrev learned about multicharged ion-collisions experiments methods and ion accelerators physics and technology.

4. As a result, Prof. R.Bruch and Prof. V.Kantsyrev initiated the foundation of a new joint project between and Lebedev Physics Institute and V /O Aviaexport / Aviatechnology from Russian side, and United States Industrial Coalition (USIC) and Lawrence Livermore National Laboratory (N Division, EBIT group) from American side. This project will start in 1997 and project is based on the results obtained in our project.

5. We are going to continue our collaboration and to extend our research program, because we have prospective, potential results and the University of Nevada, Reno and V / O Aviaexport PLC, Firm Aviatechnology wish to support a continuation of the research work of Prof. V. Kantsyrev in USA. From December 1996 he will continue a research work in the University of Nevada, Reno.

6. The benefit of the visit of Prof. V.Kantsyrev to the U.S. is an achievement of "high-tech'' advantage in the international competition and a creation of new joint projects between former defense Russian Research Institutes and particular Lawrence Livermore National Laboratory.

7. The benefit to NIS (Russia) is the possibility for Russian "High-Tech" former defense organizations to collaborate with famous American organization and to gain access to the American scientific - technical market.

III. Main goals of the project.

The main goals of the project were to construct and to test the prototypes of new optical devices for the extreme ultraviolet (EUV), soft x-ray (SXR) and x-ray spectral regions, including:

1. Prototype development of imaging, guiding and focusing short wavelength optical systems for potential Electron Beam Ion Trap (EBIT) and Electron Cyclotron Resonance (ECR) ion sources applications;

2. Prototype development of new type of spectrometer / polarimeters.

These new devices are of fundamental importance for several important problems in ion-atom collisions physics, diagnostics of plasma, x-ray microscopy, ion-surface interaction. In particular the detection of low level intensity of radiation from various sources. Using these new devices we can officially concentrate, disperse and guide short wavelength radiation and simultaneously measure the degree of polarization and optimize the shape of cross section of the photon beam for specific applications.

IV. New optical short wavelength devices for high sensitivity, high resolution spectroscopic, angular and polarization measurements using multicharged ion beams and hot plasma.

We have created new experimental instrumentation for diagnostics of hot plasma and studies of interaction of multicharged ions beams with matter (atoms, ions, molecules, microstructures, surfaces, solids) based on both glass capillary converters (GCCs) and multilayer mirrors (MLMs) or crystals, where the optical GCC device provides guiding, focusing and polarization analysis of short wavelength radiation with a large bandwidth, and the MLM or crystal optical elements are used for dispersing, focusing and polarization sensitive studies of radiation within a narrow bandwidth. In particular we report here about the development and test of such optical diagnostics devices for the spectral region 0.1 nm < λ <100 nm. This type of micro-instrumentation is very suitable also for 2D, 3D and multiparameter applications.

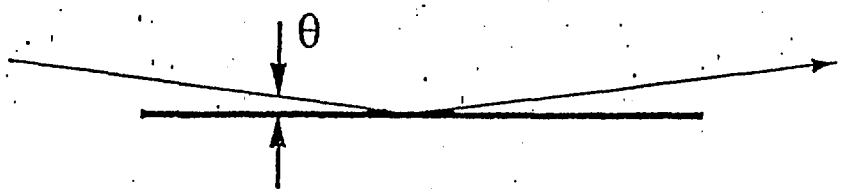
IV - 1. Introduction

Numerous existing experimental investigations are based on collecting and analyzing extreme ultraviolet (EUV) and X-ray spectra from hot plasma sources or studies of interaction of multicharged ion beams with matter. Such high resolution EUV or X-ray spectra can provide important information about the collision dynamics, cross sections and anisotropy population of magnetic substates, leading to a finite degree of polarization of the observed ionic line radiation. In these type of investigations researchers generally are challenged by weak sources of EUV or X-ray radiation or by pulsed plasma sources. Important problems of registration of short wavelength radiation to be solved are: (i) to concentrate and guide the photon emission onto a detection system, (ii) to optimize the shape of the cross section of the photon beam for specific

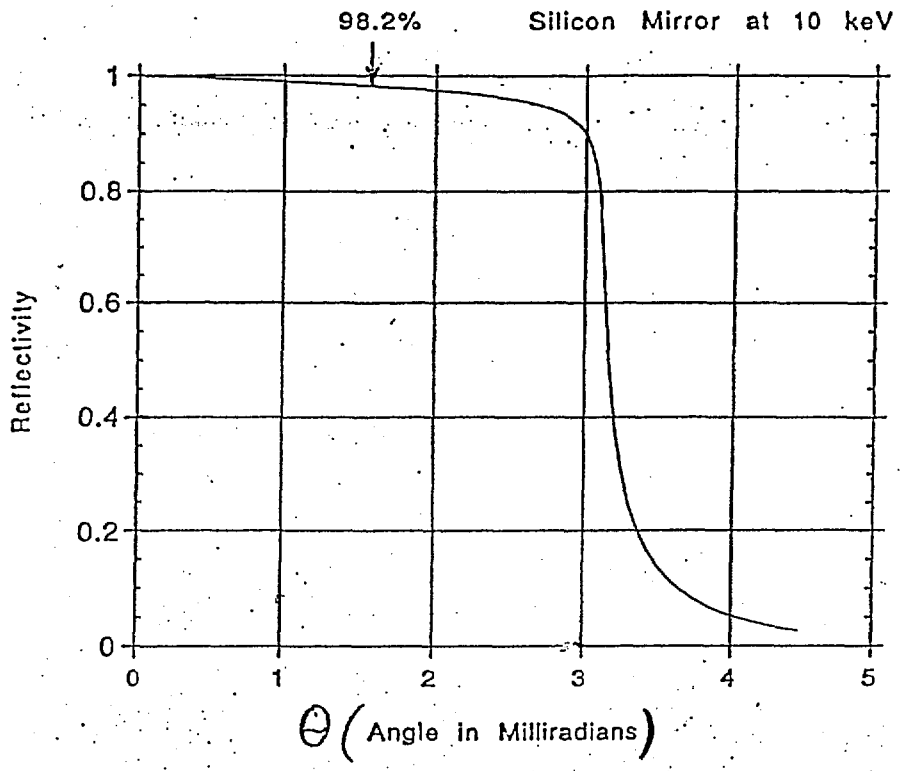
configurations of the entrance window of the detection system, (iii) to analyze the spectrum of radiation, and (iv) to measure the degree of polarization of radiation. We propose here new concepts of high sensitivity, high resolution diagnostics instrumentation based on both glass capillary converters (GCCs) and multilayer mirrors (MLMs), where the GCC devices provide guiding, focusing and polarization analysis of EUV and X-ray radiation within a large bandwidth and the MLMs are used as optical elements for dispersing, focusing and measuring the degree of polarization within a narrow bandwidth. In addition we use conventional dispersive and focusing optical elements such as diffraction gratings and crystals.

The principle of operation of typical GCC elements consisting of bundles of capillaries is based on the effect of total external reflection of radiation (Fig.1) from the inner smooth surface of glass or quartz capillaries at grazing incidence by multiple reflection (Fig.2). These devices can concentrate and guide short wavelength radiation from any source to an analyzing/detection system. The basic idea concerning a type of "light-pipe" to increase the effective solid angle of collection from a source over a long distance, has been discussed in [1]. The first experiments using single glass capillary devices took advantage of laser plasma (Fig. 3), synchrotron radiation and X-ray tubes as radiation sources [2-5]. It was shown that SXR beams with small divergence (10^{-1} - 10^{-3} rad) or SXR beams focused into a spot size of about several hundred microns can be produced. Recently several types of multicapillary devices (glass capillary concentrators - GCC) for guiding, concentrating, and transforming the shape of the cross section and the direction of X-ray beams have been constructed and tested [6-8] (Fig. 4). For the X-ray and soft X-ray spectral region we have classified the different types of GCC devices (Fig. 5) into three categories [9]: a) <u>Focusing GCCs (Concentrators)</u> for collection of radiation from a "point" source to "point" focus or to collimate the beam to quasiparallel shape [6-8] with a divergence of about 10^{-2} - 10^{-3} or from a

The total reflection optics



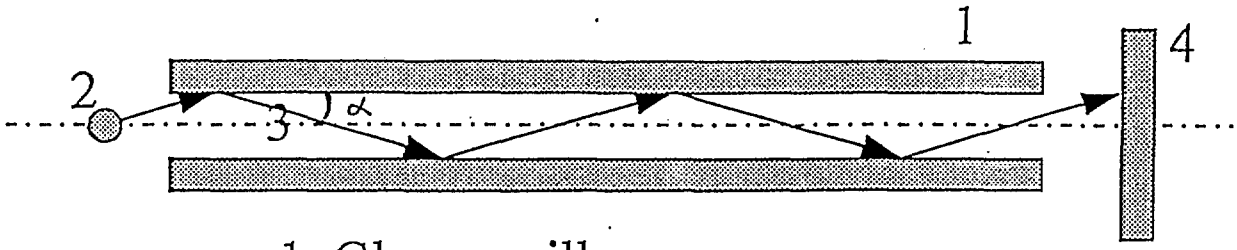
Schematic of an x ray incident on a smooth surface at angle θ reflecting specularly.



Computed Fresnel reflectance for a silicon mirror with 10 keV x rays. At half the critical angle of 3.2 mrad, the reflectance is still 98.2% (see the arrow).

Fig.1

Some Optical Properties of GCC

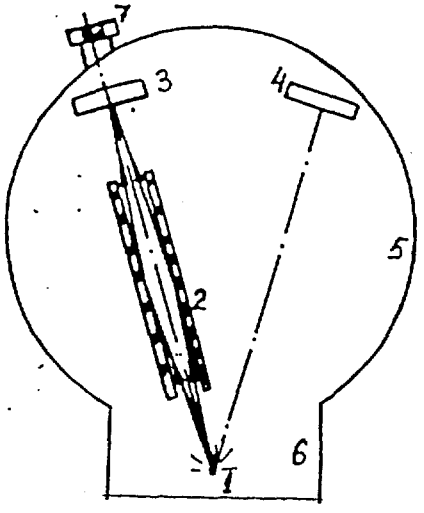


1. Glass capillary
2. Source of SXR, EUV or X-rays $\alpha < 10^\circ$
3. SXR, EUV or X-rays beam
4. Detector

Fig.2

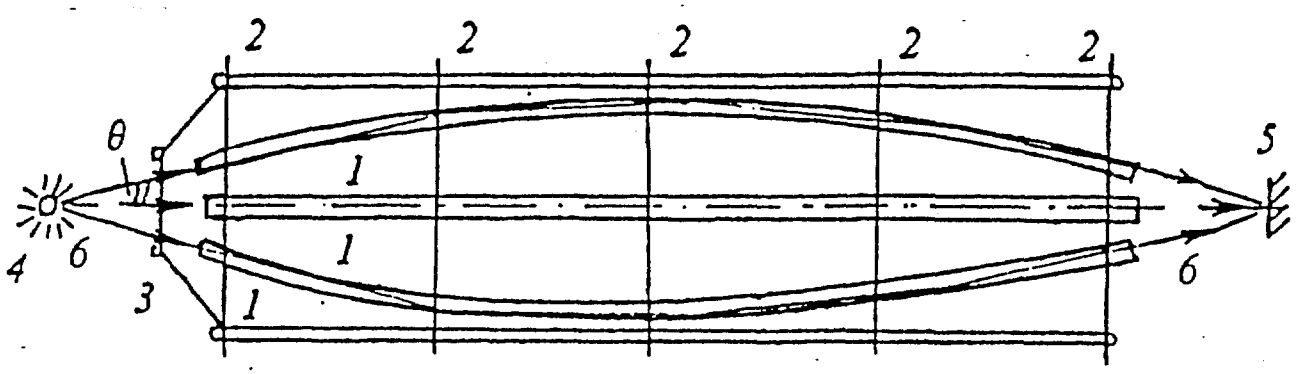
Experiments with single capillary (1974)[3]

($K_{max} \approx$ 5-10 ; $\Phi_{min} \approx$ 400-500 mcm) Moscow Phys. Eng. Inst.



1. Laser plasma ;
2. Glass capillary (l=150 mm , Φ_{inner}=1 mm)
3. Holder with film UF-VR ;
4. Control holder with film UF-VR ;
5, 6. Vacuum chambers of LPS and X-ray complex;
7. Positioning window.

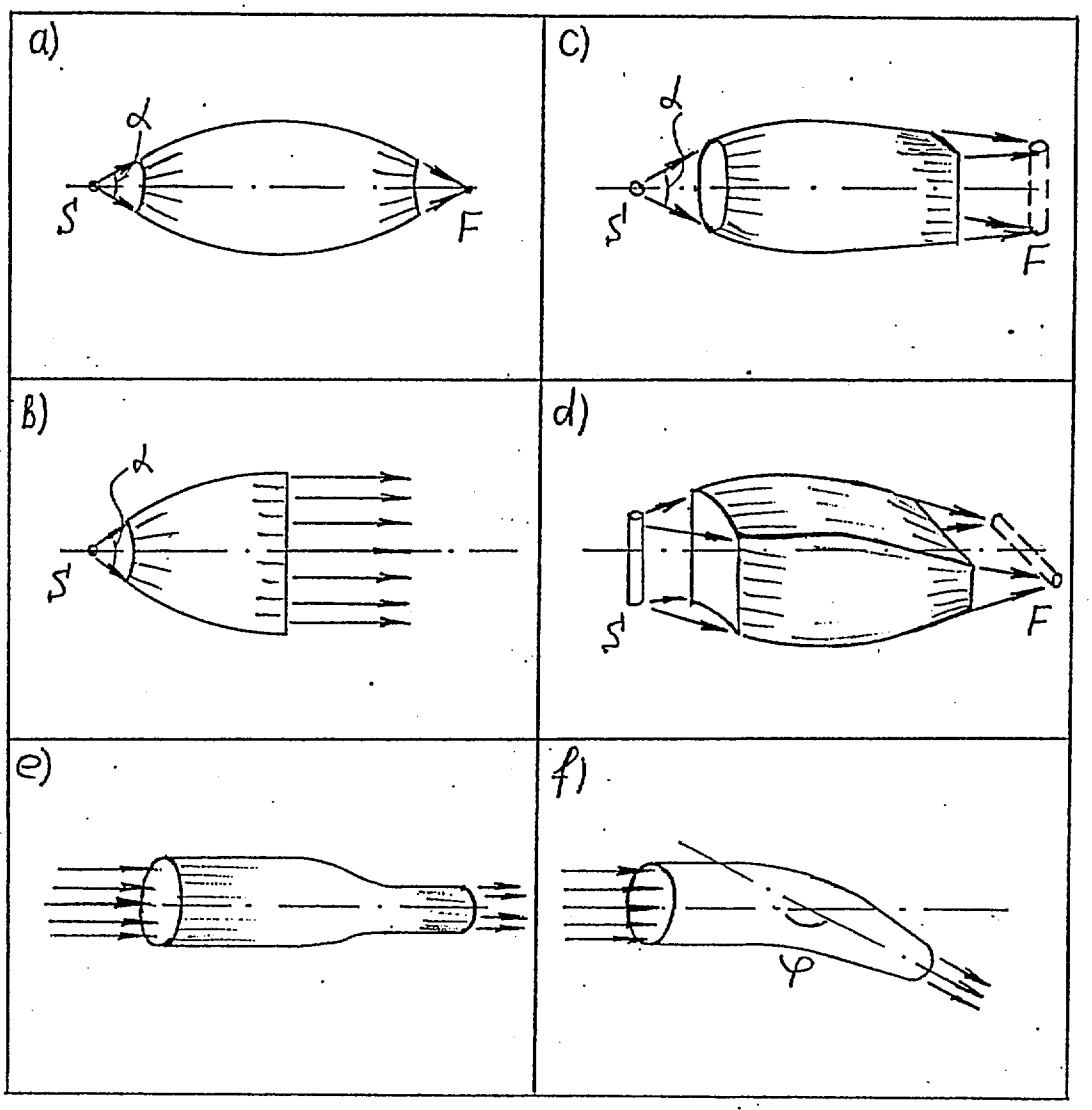
Fig.3



Schematic diagram of a focusing glass-capillary concentrator: (*1*) glass capillaries (external diameter 600 μm, internal diameter 400 μm, length 450 – 500 mm, number of capillaries $N = 500$); (*2*) support rods and perforated stops; (*3*) protection of capillaries from the effects of a plasma; (*4*) plasma source of soft x-ray radiation; (*5*) detector or irradiated object; (*6*) soft x-ray radiation.

Fig.4

12



Comparison of different type of glass capillary converters and image formation:

a) Converging lens, point to point imaging; b) Converging lens, formation of a parallel beam; c) Cylindrical lens, point to line focus; d) Cylindrical lens with 90^0 rotation of the image, line to line focus; e) concentrator with changing cross section; f) Concentrator with changing cross section and changing direction of photon beam. S: Source of radiation, F: Focus of GCC, α: Angle of collection of radiation, φ: Angle of bending of GCC.

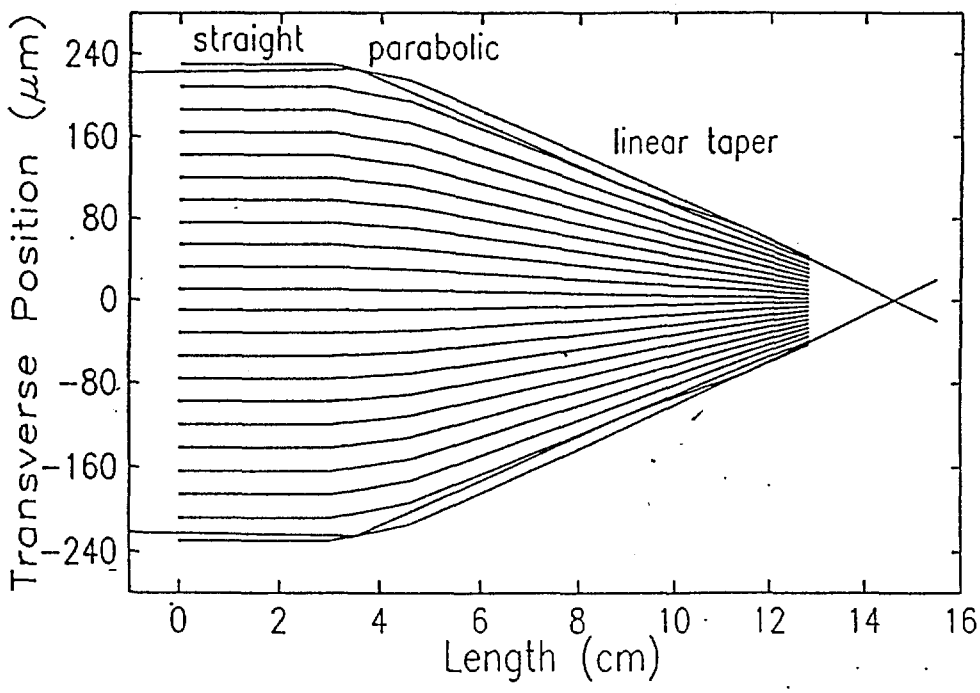
Fig.5

quasiparallel beam to a "point" focus spot; b) Focusing GCCs (Converters) with changing of the shape of the cross-section of the beam for collection of radiation from a "point" source or quasiparallel beam to a "line" shape focus or from a "line" shape source to "line" shape image (with or without rotation of the beam direction, or from "line" shape source to focus spot or quasiparallel beam [9, 10]; c) Non-Focusing Simple GCC Converters with or without changing of the shape of cross-section for basically transmitted radiation images with or without changing of the direction of the beam [11]. Two specific GCC's designs are: (i) Multicapillary GCCs (Fig.4) [6-11] produced with individual monocapillaries (or policapillaries consisting of tiny channels); (ii) Policapillary GCCs [12] with capillaries that are tapered and fused together without additional supporting frames, forming straight conical bundles of tapered channels (Fig. 6).

The second important EUV and soft X-ray optical elements used in our studies are multilayer mirrors (MLMs) which consist of highly smooth flat or spherical substrates coated with alternating layers of materials (for example, Mo/Si, W/C etc.) [13]. The thickness of such layers are several nm, and the number of layers can be up to 100 - 300. These optical elements are used at normal-incidence reflectance in the spectral region from about 3 up to 38 nm [14, 15]with a maximum coefficient of reflectance up to 60% - 70% and spectral resolution $\lambda / \Delta\lambda$ up to several ten's. In the following we describe our new x-ray and EUV optical diagnostics instruments utilizing new concepts of x-ray optic instrumentation [9, 16].

IV - 2. Polarimeter - spectrometer with GCC and MLM for soft X-ray and EUV. The existing methods to determine the degree of polarization of EUV, SXR and X-ray beams are based in general on the measurement of the difference between the coefficient of reflection of radiation with s and p polarization from optical surfaces. From dispersive elements such as flat crystals or

14



Longitudinal cross section of ideal polycapillary array with two rays traced to the point of concentration.

Fig.6

MLMs under an angle close to 45^0 [17] (Fig.7) the change of intensity of the reflected monochromatic radiation is detected by turning the crystal or MLM polarimeter over an angle from 0^0 to 90^0 along a beam axis. In some applications two spectrometers / polarimeters are used in tandem and oriented to each other at right angle. A disadvantage of this technique is that the polarization can be measured only within a limited band width, i.e. measurements are possible only for a wavelength λ near λ_o associated with the characteristic reflection angle from the given crystal or MLM close to 45^0. Our new method uses these types of polarimeters in conjunction with GCCs, MLMs, or diffraction gratings or crystals [18]. The possibility of partial changes of the polarization of SXR after multiple reflections has been analyzed theoretically for curved glass or quartz capillary [19]. Inside such curved GCC devices the **p** and **s** components of polarization are attenuated in different ways by multiply reflections and the radiation with changing ratio of **p** and **s** components can be measured. These measurements of polarization of the incident radiation are accomplished by comparing the intensity of the signal with two identical analyzer channels aligned to each other at right angles. In preliminary study we have used a non-axisymmetric GCC device curved over an angle from 45^0 to 90^0 (Fig. 8). For monochromatization of the radiation and focusing onto the entrance window of the GCC a concave MLM (3.0 nm $< \lambda <$ 30.0 nm), diffraction grating ($\lambda >$ 30.0 nm) or crystal ($\lambda <$ 3.0 nm) has been used. These optical elements practically do not alter the degree of polarization if the angle of incidence is close to normal incidence. The usefulness of such type of polarimeters has been experimentally confirmed during experiments at the Advanced Light Source (ALS) in Berkeley, where we investigated ionization - excitation processes of He by synchrotron radiation. Our prototype spectrometer / polarimeter includes a rotatable GCC device with channeltron detector and a focusing MLM. Specifically we have measured the degree of polarization of Ly α of He^+ ($\lambda = 30.4$ nm). A typical spectrum shown

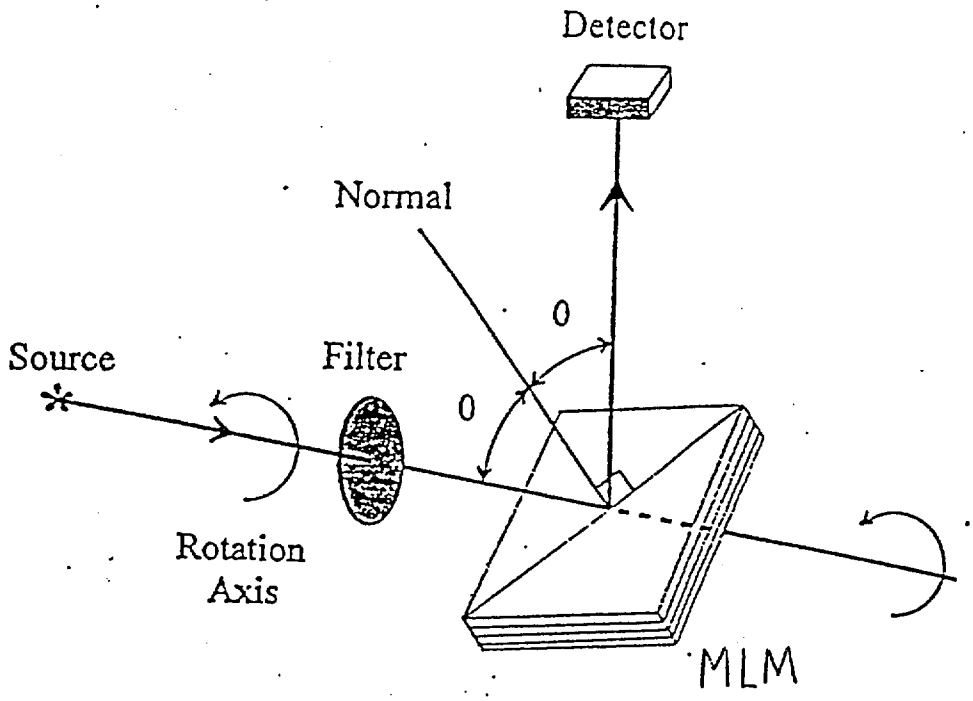


Fig.7

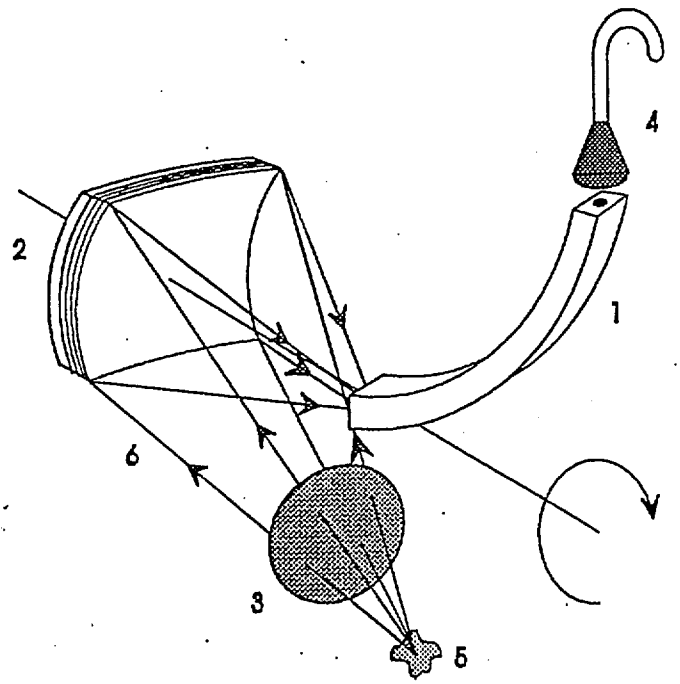


Fig.8

on Fig. 9. With this new polarimeter we have measured a degree of polarization of about 10 to 15% for the $(3s3p)^1P^0$ resonance and subsequent decay to the He^+ (2p) ionic state.

IV - 3. High sensitivity EUV spectrometer with GCC for EUV region. Recently we have developed and tested for the first time a simple focusing GCC optical system specifically designed for investigations of EUV radiation produced by electron - He collisions in a gas-cell [10](Fig.10). Here, a new more complex EUV glass capillary system has been constructed and optimized for $\lambda \cong 30.0$ nm. In this case radiation is emitted from a gas-cell subsequent multicharged to ion - He collisions. Such multicharged ion beams interacting with He gas have been delivered by the electron cyclotron resonance (ECR) ion source at the University of Nevada, Reno with ion currents in the order to 1-5 μA and projectile energies ranging from 7 keV to 110 keV. The He gas pressure in the gas-cell is of the order 0.5-2 mTorr. The distance from the gas-cell to the entrance slit of our 2.2 m McPherson-247 grazing incidence monochromator was about 600 mm. The GCC system has been constructed from 170 quartz monocapillaries with inner diameter of 0.39 mm (Fig.11). The GCC system reduces also the outstreaming of gas from the gas-cell, because the GCC was connected with the gas-cell through a flexible housing. The front and back rear focusing distances of this GCC device are 50 mm. An important design characteristic of such optical devices is concerned with the effective photon transmitting area, divided by the total illuminated area. These ratios are 7% for the entrance window of GCC and 40 % for the exit window of the GCC, respectively. The efficiency of concentration of radiation ν for the GCC system is about 10^{-2}.
(ν - efficiency of concentration of radiation by GCC, defined as the ratio of the photons reaching the rear focal area per unit time compared to the total number of photons from the source per unit time into the solid angle 4π.)

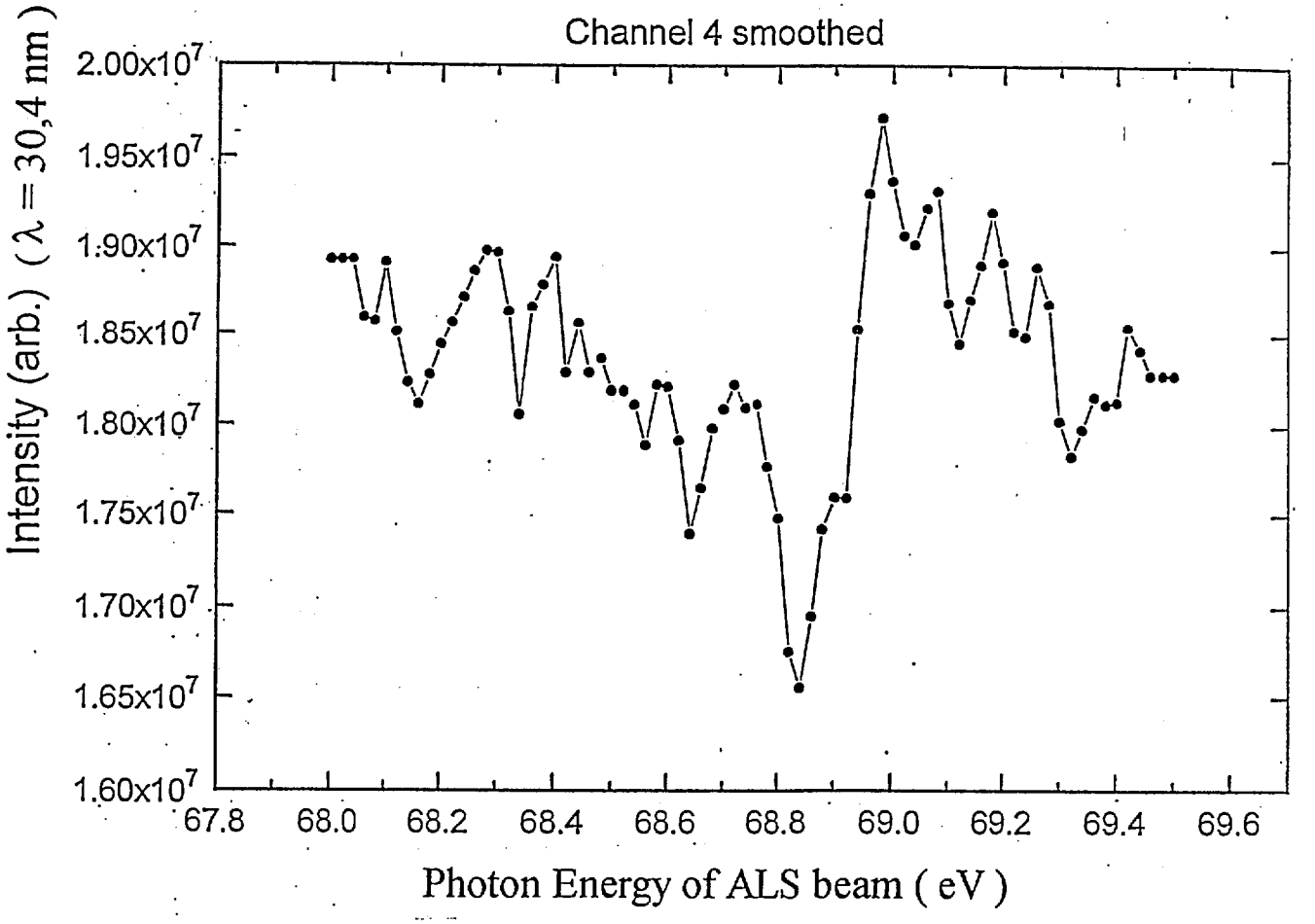

Channel 4 smoothed
Intensity (arb.) (λ = 30,4 nm)
2.00x10^7
1.95x10^7
1.90x10^7
1.85x10^7
1.80x10^7
1.75x10^7
1.70x10^7
1.65x10^7
1.60x10^7
67.8
68.0
68.2
68.4
68.6
68.8
69.0
69.2
69.4
69.6
Photon Energy of ALS beam (eV)

Fig.9

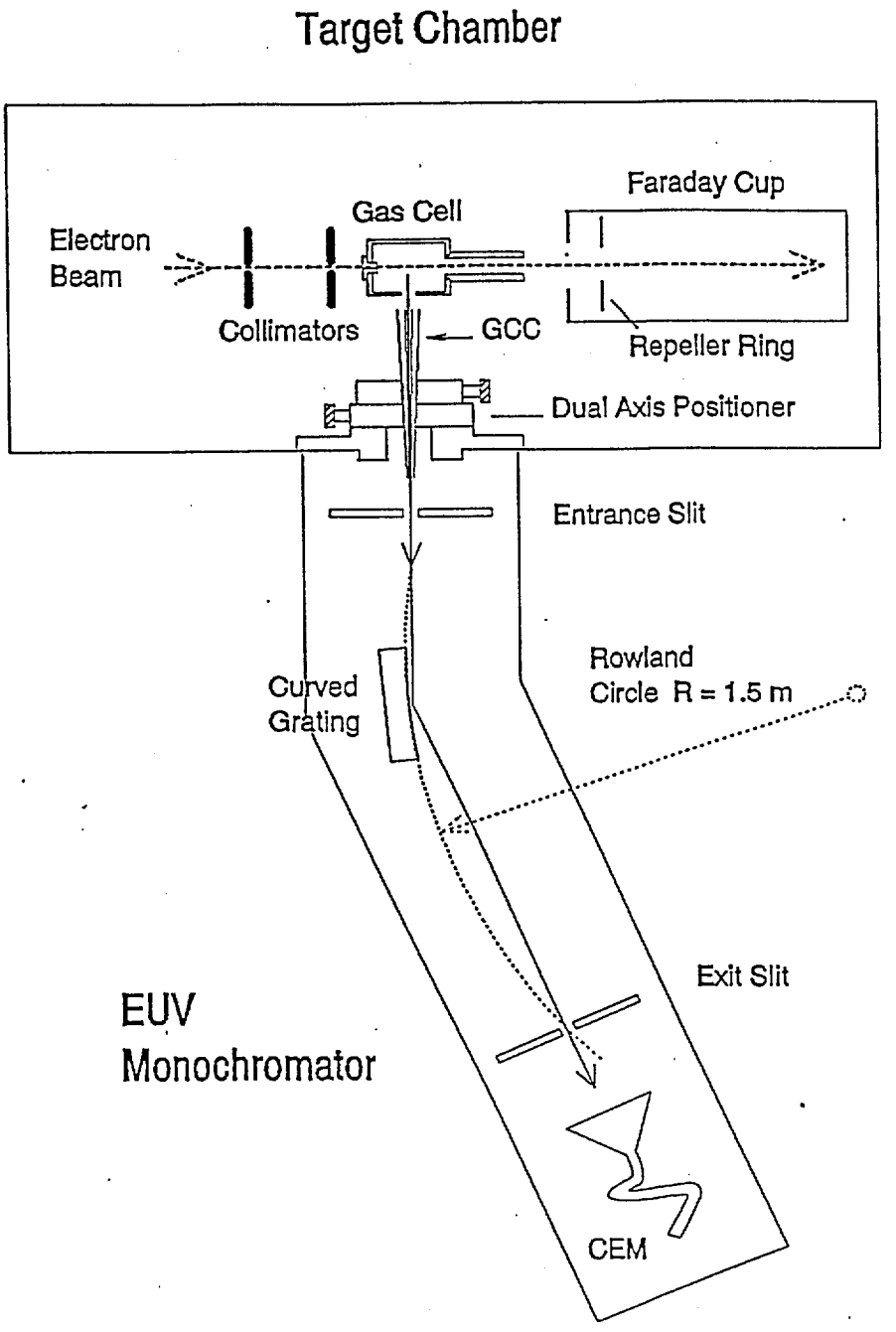
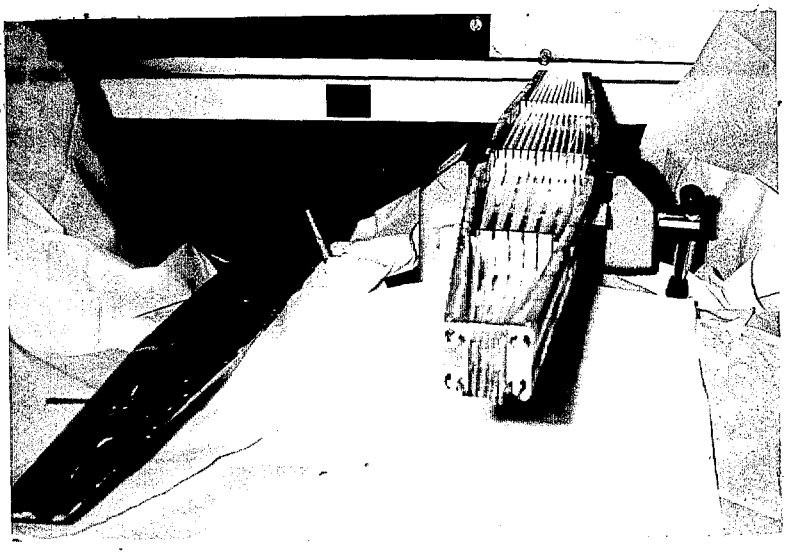

Target Chamber
Faraday Cup
Gas Cell
Electron
Beam
Collimators
GCC
Repeller Ring
Dual Axis Positioner
Entrance Slit
Rowland
Circle R = 1.5 m
Curved
Grating
Exit Slit
EUV
Monochromator
CEM

Fig.10



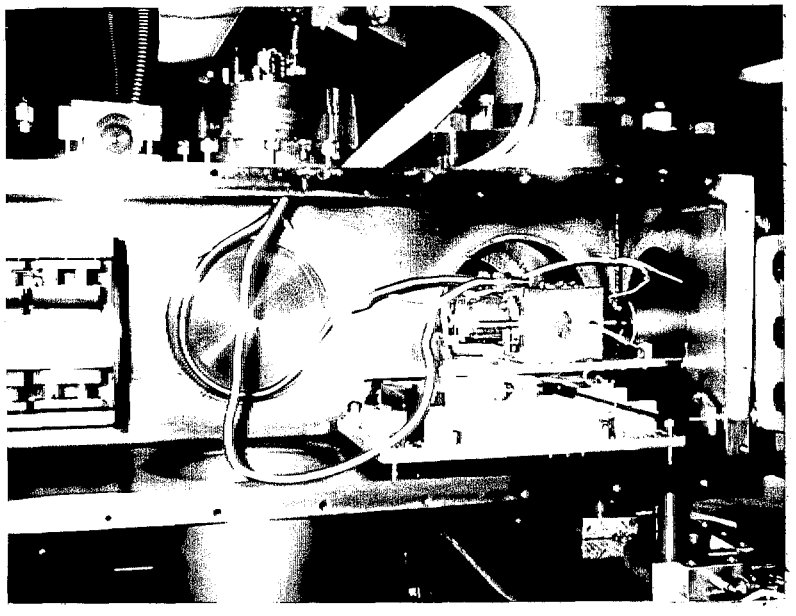
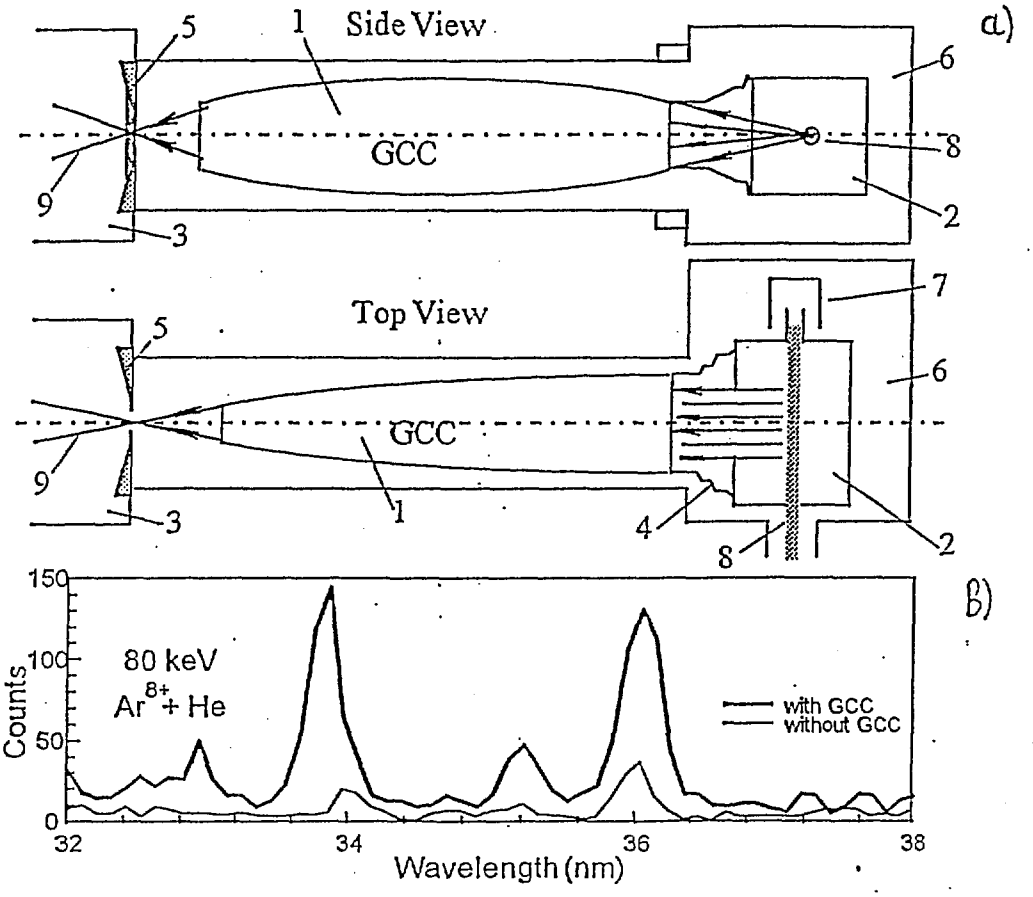


Fig.11

With this GCC system we can collect radiation from a horizontal ion beam segment ("line source") with an effective diameter smaller than 2 - 4 mm and a maximum length of about 20 mm, guide, rotate and focus this radiation beam onto a vertical rectangular area of $0.8x10mm^2$ ("line focus") at the entrance slit of the monochromator. We note that we have partially interchanged the capillaries at the exit of the GCC to improve a uniform irradiation of the monochromator entrance slit. The GCC optics is mounted on an adjustable holder in a special vacuum chamber between the target chamber and the monochromator (Fig.12).

Experimental results determined for the coefficients of enhancement η are shown in Table 1. (η - coefficient of enhancement of the flux density of radiation reaching the detector, defined as the ration of EUV flux density in the focus area with and without GCC). Specifically we used strong well resolved spectral lines , e.i. O^{6+} ($\lambda \approx 15.0$ nm), He^+ ($\lambda = 30.4$ nm), He ($\lambda = 58.4$ nm) and O^{6+} ($\lambda \approx 103 - 105$ nm) to obtained the enhancement factor η. It is evident that the GCC operates reasonably well in a wavelength region from 10 to about 100 nm [16, 20] (Fig.13). In this study we have demonstrated substantial enhancement of EUV radiation. Under optimal experimental conditions even larger enhancement factors η larger than 30 may be obtained for such complex GCC type "line source - line focus" devices in the EUV region. For shorter wavelength experimental value of $\eta \approx 100$ [21] have been obtained in region 0.8 - 1.0 nm for GCC type "point source - point focus" type. In the set-up used above the observed Doppler broadening with GCC for projectile spectral lines is approximately 5% to 10%. This broadening results from a 5^0 angular acceptance angle of the capillaries in our experiment.

13



a) Schematic diagram of EUV spectrometer with complex GCC device; b) Typical EUV spectrum in the wavelength range from 32 to 38 nm produced by Ar^{8+} + He collisions at 80 keV: ——— with GCC, ——— without GCC. 1. GCC, 2. Gas cell, 3. Grazing incidence monochromator, 4. Flexible housing, 5. Monochromator entrance slit, 6. Target chamber, 7. Faraday cup, 8. Ion beam, 9. EUV radiation

Fig.12

The dependence of η for GCC as a function of the wavelength

λ (nm)	η
15.0	7.0±0.5
30.4	10.0 ±1.0
58.4	5.0±1.0
104.0	1.7±0.5

Table 1

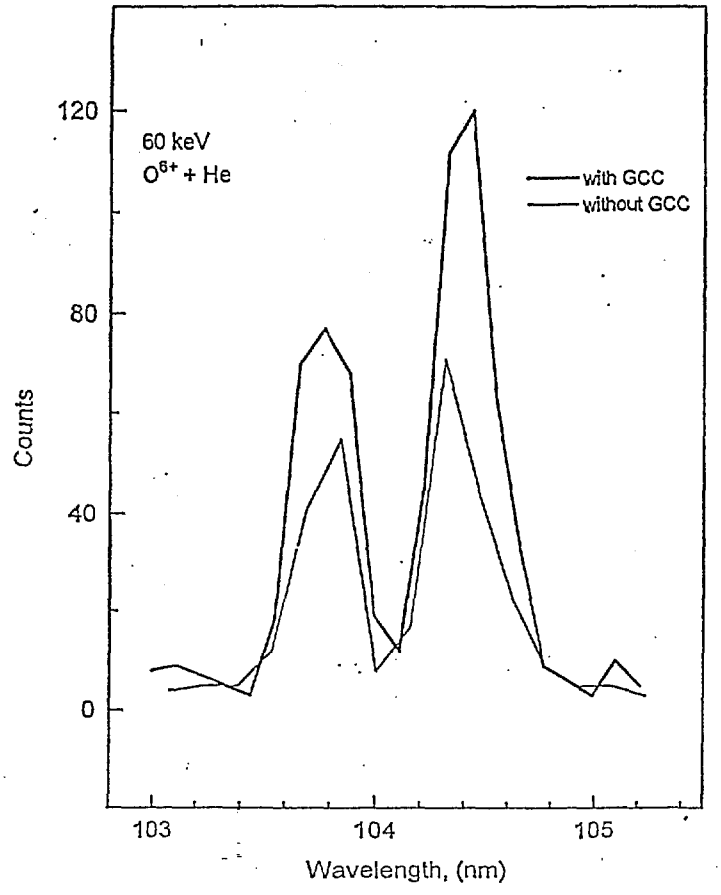


Fig.13

IV - 4. Application of new optical devices for spectroscopic studies of interaction of multicharged ion beams with gaseous targets in the EUV region.

Here we have continued our efforts to apply the new complex GCC device, specifically developed for the EUV region to increase the spectral sensitivity of our optical instrumentation. In particular we have studied EUV spectra arising from He^{+} + He, He^{2+} + He, C^{4+} + He, N^{5+} + He, O^{6+} + He, Ar^{8+} + He and Ar $^{11+}$ + He collisions with and without GCC system.

In Fig. 14a we have displayed a high resolution spectrum produced in 20 keV He^{2+} +He collisions[9, 22]. The line structures observed originate from photon decay of the He^{+} (np) target states. As can be seen the He^{+} (np) -> 1s transitions with n up to 5 are clearly resolved. The signal statistics in Fig. 14 a has been dramatically increased owing to the GCC device used. The enhanced sensitivity and keep resolution allows us to perform the first detailed studies on transfer - excitation in slow ion-helium collisions [23] with state selective observation of the exited He^{+} (np) states with $n \geq 3$. The He^{2+} + He collision system is one of the most fundamental test cases where the role of one and two electron processes can be studied. In this work we have been particularly interested in the population of target as well as projectile He^{+} (np) states, which can not be distinguished under 90 degree observation. Such states may be produced by the following processes:

<u>One-Electron Capture</u>

He^{2+} (P) + He ($1s^2$, T) -> He^{+} (np, P) + He^{+} (1s, T) ; (1)

26

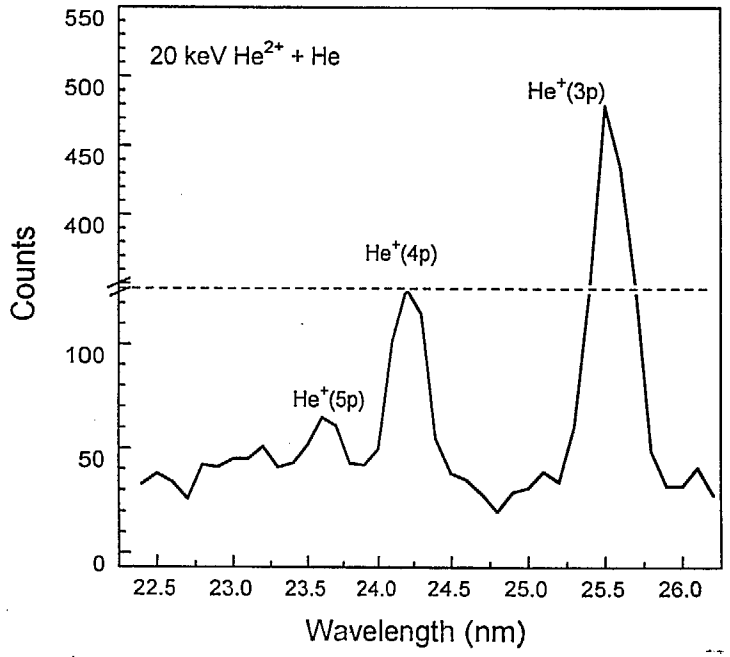


Fig.14 a

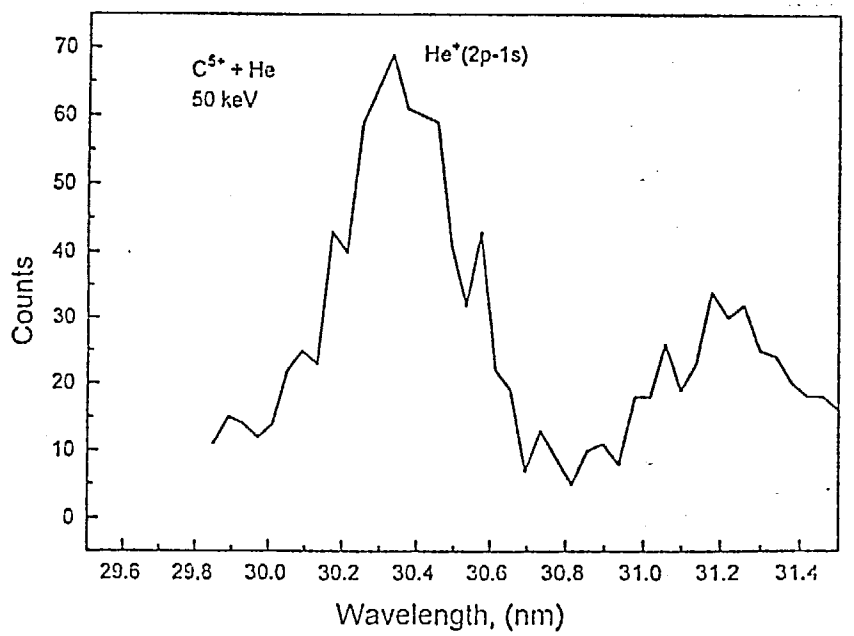


Fig. 14 b

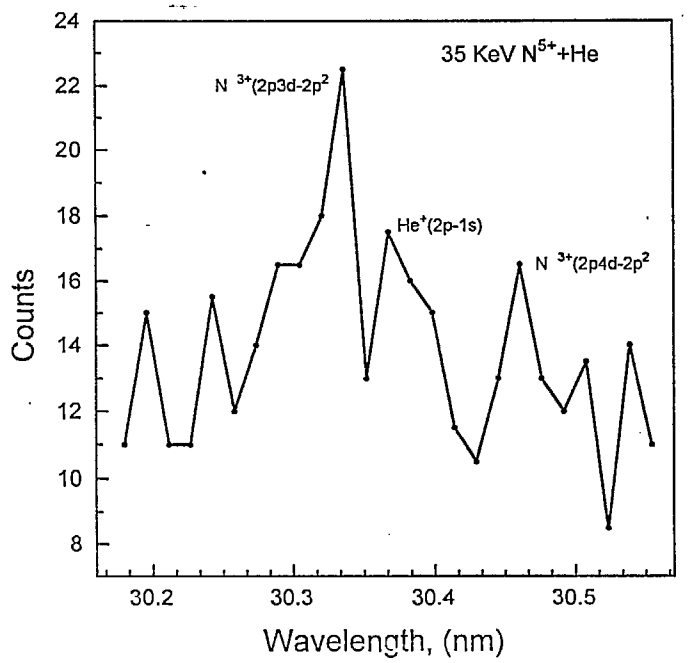


Fig. 14 c

Capture Plus Simultaneous Excitation of the Target Ion

He^{2+} (P) + He ($1s^2$,T) -> He^+ (1s, T) + He^+ (np, P); (2)

Single Ionization and Simultaneous Excitation of the Target Ion

He^{2+} (P) + He ($1s^2$,T) -> He^{2+} (np, T) + e^-. (3)

Here P and T represent the projectile and target atom respectively. From our data we have deduced He^+ (np) emission cross sections normalized to the 2p cross section of Folkerts et. al. [24]. Our 3p and 4p results at 20 keV impact energy (5 keV amu^{-1}) are in excellent agreement with the data from [24]. For He^+ (5p) we report here the first cross section, namely σ (5p) = 0.45 x 10^{-18} cm^2.

Similar high-resolution EUV measurements in the vicinity of the 30.38 nm line were carried out for C^{5+} + He collisions at a collision energy of 50 keV [20, 25]. The EUV spectrum measured with resolution of 60 is presented in Fig. 14 b . The He^+ line is evident in this spectral region, with a measured emission cross section 3.8 times larger than for C^{4+} + He at 40 keV. From these measurements, the cross section for single electron capture accompanied by target excitation in C^{5+} + He collisions is estimated to be 4 x 10^{-17} cm^2 at 50 keV.

Another striking example is a spectrum in the 30.18 to 30.56 nm wavelength range following 35 keV N^{5+} + He collisions (see Fig.14c)[20]. The main spectral features in this figure stem from N^{3+} (2lnl') initial projectile states with n = 3 and 4. These states have been populated by double electron capture processes. In addition the He^+ (2p)$\rightarrow$1s line due to ionization plus excitation and capture plus excitation is resolved. In this connection we note that

the high wavelength resolution obtained with the GCC in this work ($\lambda / \Delta\lambda \approx 500$) represents a large improvement over previous results by de Heer and coworkers [10-11].

New measurements were also made for the O^{6+} +He collision system at an energy of 60 keV with spectral resolution 200 [25]. In this case, for which the measurements are presented in Fig. 15 a , the measured spectrum is rich in partially resolved lines that are extremely close to the 30.38 nm He^{+} line, making it nearly impossible to extract a relative cross section for the capture-plus-target -excitation process. It was found in this case that several of the observed lines are not tabulated in the compilation by Kelly [26]. The analysis of new spectra will be published in [25].

In addition we have measured EUV spectra with and without new GCC for 80 keV Ar^{8+} + He collisions. The obtained spectra are indicated in Fig.15 b. The most pronounced peaks are labeled 1 to 18. In Table 2 [27] we give the line assignment of the most dominant features. We also compare our results to previous collisional studies by Bliman and coworkers [28]. As can be seen the most prominent lines originate from single electron and double electron capture processes leading to Na-like 1s2nl singly excited states and Mg-like doubly excited states. Finally we nout that our Ar spectra reveal more detailed structure than previously reported data from Bliman and coworkers [28] due to our higher wavelength resolution and enhanced sensitivity of new GCC optics set - up.

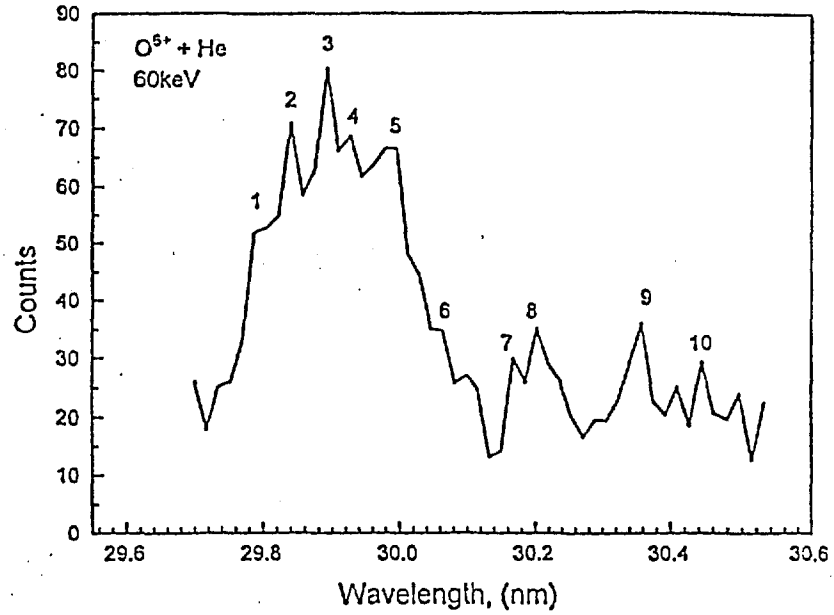


Fig.15 a

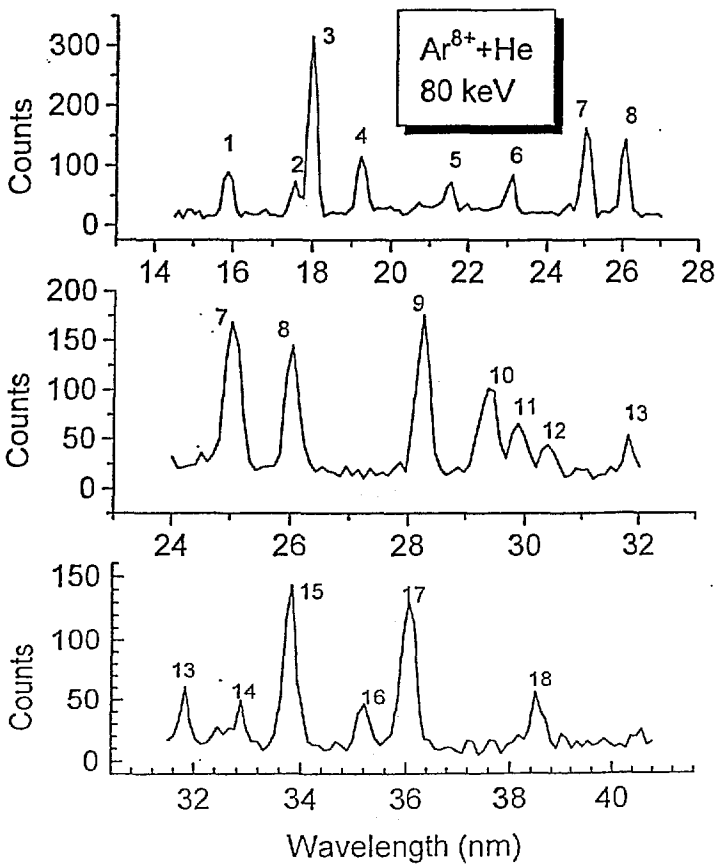


Fig. 15 b

Peak	Ion	Transition	Present Paper	Bliman et al	Kelly
			λ(nm)	λ(nm)	λ(nm)
1	Ar^{7+}	$4p\ ^2P \rightarrow 3s\ ^2S$	15.90	15.90	15.892 15.918
2	Ar^{6+}	$3s4p\ ^1P \rightarrow 3s^2\ ^1S$	17.54	17.54	
3	Ar^{7+}	$4d\ ^2D \rightarrow 3p\ ^2P$	18.00	18.00	17.940 18.025
4	Ar^{6+}	$3s4d\ ^3D \rightarrow 3s3p\ ^3P$	19.20		19.204 19.204
5	Ar^{6+}	$3s4d\ ^1D \rightarrow 3s3p\ ^1P$	21.60	21.56	
6	Ar^{7+}	$4s\ ^2S \rightarrow 3s\ ^2P$	23.10	23.10	22.944 23.088
7	Ar^{6+}	$3s4s\ ^3S \rightarrow 3s3p\ ^3P$	25.10		24.9886 25.0940
8	Ar^{7+}	$4f\ ^2F \rightarrow 3d\ ^2D$	26.00	26.03	26.025 26.033
9	Ar^{6+}?	$3s4s\ ^1S \rightarrow 3s3p\ ^1P$	28.25	28.14	
10	?		29.40		
11	Ar^{6+}	$3s4f\ ^3F \rightarrow 3s3d\ ^3D$	29.80		29.766 29.770
12	He^{+}	$2p\ ^2P^{o} \rightarrow 1s\ ^2S$	30.38		
13	?		31.80		
14	?		32.80		
15	Ar^{7+}	$4p\ ^2P \rightarrow 3d\ ^2D$	33.80	33.80	33.726
16	Ar^{6+}?	$3s4f\ ^1F \rightarrow 3s3d\ ^1D$	35.20	35.20	
17	?		36.00		

Table 2

V. The potential applications of new optical devices for EBIT and other sources of multicharged ions. The commercial potential of this project.

The basic characteristics of the development of new optical devices and systems for applications are summarized in Table 3. Such devices as spectrometers / polarimeters, monochromators, compact spectrometers allow to perform spectroscopic and polarimetric measurements in a wide spectral range of wavelength $\lambda < 50.0$ nm. For example, we intend to use the high resolution Hamoshi x-ray spectrometer already working at EBIT of LLNL [29], by using an additional GCC focusing and guiding element, which allows to decrease the period of measurements by factor more than 10 (Fig.16).

As displayed in Fig. 16 the imaging systems and optical filters for blocking of hard x-ray [21] are intended to transmit an image for EUV, SXR or x-ray spectral regions for studying the structure of emitting region of the EBIT source. A similar type of device has been used early to produce an image of the hot plasma [9 , 11, 21]. To produce a two dimensional image of the plasma region of the EBIT of LLNL source we will build a new imaging and optical filter system with GCC including a focusing zone plate and a CCD imaging detector.

These photon guiding and focusing systems are intended to transmit flux of quanta from a source onto a detector. In this way we can substantially enhance the solid angle leading to an attenuation coefficient proportional to about 1/r, where r is the distance from the source to the detector. In

Table 3 Main Properties of Optical Devices For EUV, SXR and X-Ray Spectral Regions.

Optical Devices	Wave-length Range λ	Main Optical Elements	Physical Principle	Spectral Resolution λ/Δλ	Possibility of Focusing of Radiation	Band Width	Source of Radiation	Type	Vacuum Required	Field of Application	Commercial Potential	Paten-table
1	2	3	4	5	6	7	8	9	10	11	12	13
Spectrometer-Polarimeters	>350 Å	Spherical Mirror Elements with Grating	Normal or Grazing Incidence	<500	Yes	Narrow	EBIT, ECR Ion Sources, Laser and Discharge Plasma Sources, Synchrotron Radiation, Collisional, Space Astrophysical Sources, Fusion	Multi channel Wave-length Selective	HV UHV	EUV Spectrometry and Polarimetry, Angular Distribution, Surface Analysis, Molecular Physics, Atomic Physics	Spectroscopic Instrumentation, Space Technology, Plasma Diagnostic Instrumentation EUV Optics	Yes
Compact Spectrometers	50 to 500 Å	Grating	Grazing Incidence	<500	Yes	Broad	—"—	Multi channel	HV UHV	EUV Spectrometry Angular Distribution, Coincidence Experiments, Atomic Physics	Spectroscopic Instrumentation, Surface Analysis, EUV and SXR Optics	Yes
Spectrometer-Polarimeters	50 to 350 Å	GCC with MLM or Grating	Normal Incidence	> 20	Yes	Broad	—"—	Single channel Wave-length Selective	HV UHV	EUV Spectrometry and Polarimetry Angular Distribution Surface Analysis Coincidence Experiments	Spectroscopic Instrumentation, Space Technology, Capillary Optics, EUV and SXR Optics	Yes
Mono-chromators	50 to 350 Å	MLM	Normal Incidence	> 20	Yes	Broad	—"—	Multi channel Wave-length Selective	HV UHV	EUV Spectrometry, Surface Analysis, Atomic Physics	Plasma Diagnostics Instrumentation, Space Technology, EUV, SXR Optics	No
Spectrometer-Polarimeters	<30 Å	Crystal with simple GCC	Bragg Reflection	> 1000	Yes	Narrow	—"—	Multi channel	HV MV	Precision SXR, X-Ray Spectrometry and Polarimetry, Atomic Physics	Spectroscopic Technology, Space Technology, Capillary Optics, Plasma Diagnostics X-Ray Optics	Yes
Spectrometers	<30 Å	Crystal	Bragg Reflection	> 2000	Yes	Super Narrow	—"—	Multi channel	MV LV	High Precision Spectroscopy, Atomic Physics	Spectroscopy Technology, X-Ray Optics	No

Table Footnote:

MLM: Multilayer Mirror
GCC: Glass Capillary Converter
EUV: Extreme Ultra Violet
SXR: Soft X-Ray

EBIT: Electron Beam Ion Trap
ECR: Electron Cyclotron Resonance Ion Source
UHV: Ultra High Vacuum
HV : High Vacuum
MV : Medium Vacuum
LV: Low Vacuum

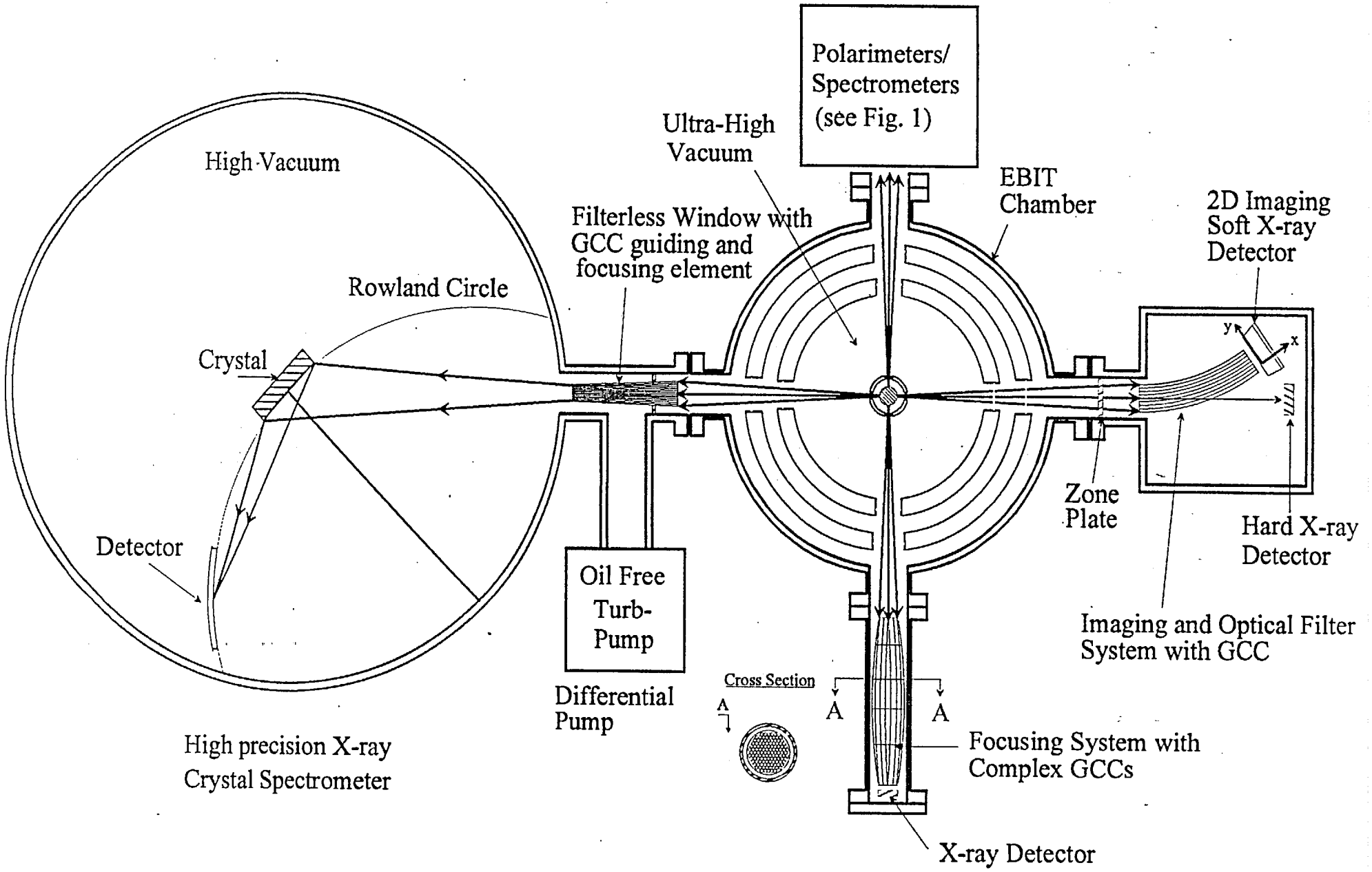
Table 3(continued)

Optical Devices	Wave-length Range λ	Main Optical Elements	Physical Principle	Spectral Resolution λ/Δλ	Possibility of Focusing of Radiation	Band Width	Source of Radiation	Type	Vacuum Required	Field of Application	Commercial Potential	Paten-table
1	2	3	4	5	6	7	8	9	10	11	12	13
Imaging Systems	Wide range ≤350 Å	GCCs or MLMs	Multi Reflections inside Poly-Capillary System, Reflection form MLM	-	Yes	-	EBIT, ECR Ion Sources, Tokamak, Solar Source, Laboratory and Astrophysical Plasma Sources	Multi channel	All Ranges	Imaging, Plasma Diagnostics, Medical and Biological Applications, X-ray Microscopy, Crystallography, Topography	EUV and X-ray Optics, Capillary Optics, Medical and Biological Instrumentation	Yes
Photon Guiding	Wide range ≤350 Å	GCCs	Multi Reflections inside Mono- and Poly-Capillary System	-	No	-	EBIT, ECR Ion Sources, Tokamak, Solar Source, Laboratory and Astrophysical Plasma Sources	Multi channel	All Ranges	Plasma Diagnostics, Medical and Biological Applications, Spectroscopy, Crystallography, Topography	Instrumentation for Surface Physics, Surface and Material Analysis	No
Focusing Systems	Wide range ≤350 Å	GCCs or MLMs	Multi Reflections inside Mono- and Poly-Capillary System, Reflection from MLM	-	Yes	-	EBIT, ECR Ion Sources, Tokamak, Solar Source, Laboratory and Astrophysical Plasma Sources, All types of Fluorescent Sources	Multi channel	All Ranges	Surface Radiation Physics and Plasma Physics, Spectroscopy, Medical and Biological Applications, Topography, Crystallography, Material Analysis	Instrumentation for Surface Physics, Surface and Material Analysis, EUV and SXR Optics, Capillary Optics, Medical and Biological Instrumentation	No
Optical Filters for Hard X-Ray	≤350 Å	GCCs MLMs Foils	Multi Reflections inside Poly-Capillary System, Reflection from MLM	-	Yes	-	EBIT, ECR Ion Sources, Tokamak, Solar Source, Laboratory and Astrophysical Plasma Sources	Multi channel	All Ranges	Plasma Diagnostics, Spectroscopy, Medical and Biological Applications, Crystallography, Topography	Capillary Optics, Vacuum Technology, Medical and Biological Instrumentations	Yes
Filterless Windows	Wide Range ≤350 Å	GCCs	Multi Reflections inside Poly-Capillary System	-	No	-	EBIT, ECR Ion Sources, Tokamak, Solar Source, Laboratory and Astrophysical Plasma Sources, All types of Fluorescent Sources	Multi channel	UHV HV MV	Differential Pumping for Synchrotron Radiation, Tokamak and Plasma Applications, Crystallography, Topography	Plasma Diagnostics, Vacuum Technology, Medical and Biological Instrumentation	Yes

Table Footnote:

MLM: Multilayer Mirror
GCC: Glass Capillary Converter
EUV: Extreme Ultra Violet
SXR: Soft X-Ray

EBIT: Electron Beam Ion Trap
ECR: Electron Cyclotron Resonance Ion Source
UHV: Ultra High Vacuum
HV : High Vacuum
MV : Medium Vacuum
LV: Low Vacuum



Plasma Diagnostics in EBIT

Fig.16

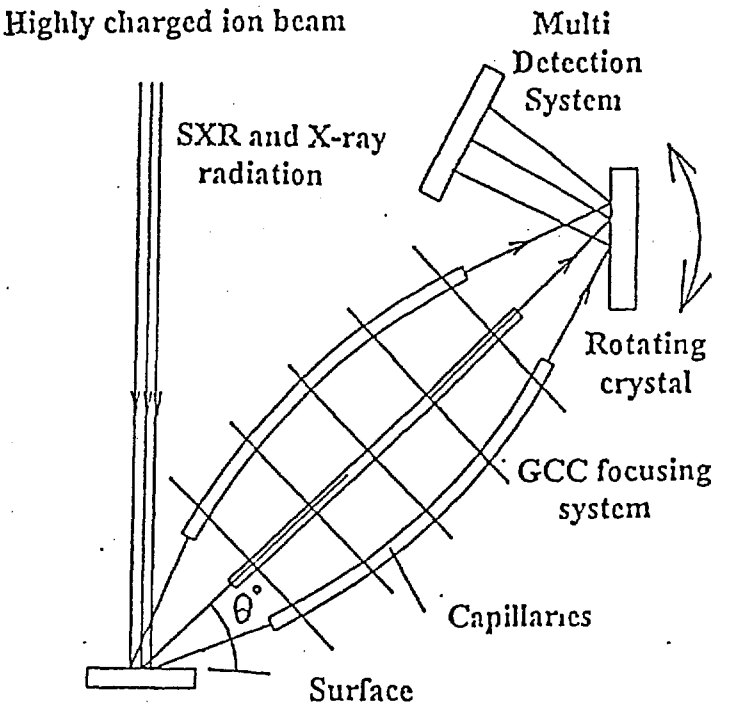
35

Fig.16 we have shown that filterless windows can be used as new optical elements based on GCC [18]. Such elements can be applied for EUV and x-ray with a transmission coefficient up to 50 - 70 %. These elements provide also a differential pumping between regions of ultrahigh and high (or middle) vacuum and have been used, for example, in experiments with ECR sources [9, 16, 20, 25, 27] and will use for synchrotron radiation and other ultrahigh vacuum facilities such as EBIT.

The possible layout of new instrumentation constructed for ion - surface analysis using ion beam extracted from EBIT source, is shown in Fig.17. The measurements for SXR and x-ray regions can be performed by means of large solid angle, rotating spectrometer with GCC system.

The possible areas of applications for these complex instrumentation and diagnostics tools are angle and space resolved accurate EUV spectrometry and polarimetry for surface analysis, coincidence experiments, ionic spectroscopy, plasma diagnostics, crystallography, topography, medical and biological applications, including x-ray microscopy, x-ray lithography (see Table 3).

The commercial potential of this proposal involves the design production and marketing of new type of EUV and x-ray optics, instrumentation for spectroscopy, space technology, plasma diagnostics, surface analysis, bio-medical instrumentation, vacuum technology and material science.



Large solid angle
rotating surface analysis
spectrometer with GCC
focusing and quiding system
and crystal for SXR or
X-ray radiation.

Ion-surface analysis instrumentation for EBIT

Fig.17

VI. Conclusion

We have demonstrated that complex GCC short wavelength optics can dramatically enhance collisional EUV spectra arising from multicharged ion-atom collisions. This new method is suitable not only for high resolution collisional spectroscopy but also for accurate cross section measurements and plasma diagnostics applications. The technique is equally suited for studies of interaction of multicharged ionic and atomic beams with synchrotron radiation providing enhanced sensitivity for example for multiparameter coincidence experiments or high resolution precision spectroscopic investigations.

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VIII. List of Publications

1. **Kantsyrev V., Bruch R., New optical methods for short wavelength hot plasma diagnostics.** Rev. Sci. Instr., **68**, 1 (1997), in press.

2. **Bruch R., Kantsyrev V.,** Golovkina V., Shlyaptseva A., Golovkin I., Phaneuf R., Schneider D., **Application of high-resolution, high-sensitivity spectrometry in the extreme ultraviolet wavelength range for diagnostics of single and double electron capture processes in He^{2+} + He and Ar^{8+} + He collisions.** Rev. Sci. Instr., Instr., **68**, 1 (1997), in press.

3. **Kantsyrev V., Bruch R., New concepts of compact, high sensitivity, high resolution diagnostics instrumentation for spectroscopic, angular and polarization measurements in the EUV, SXR and X-ray range using multicharged ion beams and hot plasma.** Phys. Scripta (1997), in press.

4. **Bruch R., Kantsyrev V.,** Phaneuf R., Golovkina V., Shlyaptseva A., Golovkin I., **New spectroscopy technique using glass capillary converters (GCCs) for study of interactions of multicharged ions with gaseous targets in the extreme ultraviolet (EUV) region.** Phys. Scripta (1997), in press.

5. Phaneuf R., **Bruch R.,** Da X., Golovkina V., Golovkin I., **Kantsyrev V.,** Li H., Rejoub R., Shlyaptseva A., Swenson J.K., **Photon and electron emission experiments at the University of Nevada, Reno multicharged ion facility.** Proc. XIV Intern. Conf. on the Application of Accelerators in Research and Industry, Denton, USA (1996), in press.

6. **Bruch R., Kantsyrev V., New concepts of compact high sensitivity, high resolution diagnostics tools for spectroscopic and polarization measurements in the EUV, SXR and X-ray range using accelerators.** Proc XIV Intern. Conf. on the Application of Accelerators in Research and Industry, Denton, USA (1996), in press.

42

IX. List of Patent Applications

1. Kantsyrev V., Bruch R., Shlyaptseva A., **Measurements of polarization and spectral characteristics of beams of EUV, SXR and X-ray radiation**, patent application, reg. No. 34,778, field March 30, 1996.

43

X. List of Conferences

1. The 11th topical conference "High - temperature plasma diagnostics", Monterey, California (USA), May 1996. - Two posters.
2. The DAMOP Annual Meeting. Ann Arbor, Michigan (USA), May 1996. - Two posters.
3. The Eighth International Conference on the Physics of Highly Charged Ions (HCI 96), Omiya, Saitama (Japan), September 1996. - Two posters.
4. XIV International Conference on the Application of Accelerators in Research and Industry, Denton (USA), November 1996. - One invited talk, two posters.

44

XI. The Financial Report

1. Living expenses for twelve months	$ 13,500
($ 1,125 per month)	
2. International Travel was include in living expenses	$ 0,000
3. Scientific Supplies Optical elements	$ 1,500
TOTAL	$ 15,000

45

APPENDIX

Glass Multicapillary Optics: Creation and Development (excluding microchannel arrays)

Prepared by Prof.V.Kantsyrev (UNR, Reno, NV).

Tittle	Authors, ref., country	Years
1.The effect of total outer reflection of x-Ray at grazing incidence.	A.Compton [1]	1923
2.The idea of x-Ray „light pipe"	P.Pound , G.Rebka [2](USA)	1959
3.The first experiments for guiding and focusing of soft x-ray (SXR) from laser-plasma source by single glass capillary and Certif. of Authorship (USSR) for device for guiding and focusing of SXR from point source to quasiparallel beam or point focus using the effect of total outer reflection.	F.Mallozzi, H.Epstein, R.Jung et al. [3](USA). O.Ananyin, Yu.Bykovsky, V.Kantsyrev et al. [4].(USSR)	1974
4.The first applications of laser plasma source of SXR for medicine and biology, - including applications of glass capillary for guiding and focusing SXR.	F.Mallozzi, H.Epstein R.Jung et al. [3](USA). O.Ananyin, Yu.Bykovsky V.Kantsyrev et al.[5,6] (USSR)	1974 - 1978
5.The investigations of the properties of a single capillary for x - ray and SXR regions (0,1A < λ < 50 A).Period from 1976 to 1989 up to creation of multicapillary converters.	D.Mosher, S.Stephanakis [7] (USA)	1976
	W.Vetterling, R.Pound [8] (USA)	1976
	P. Chung, R.Pantell [9] (USA)	1977
	Yu.Bykovsky, V.Kantsyrev et al. [6](USSR)	1978
	Yu.Bykovsky, V.Kantsyrev, Yu.Kozyrev [10](USSR)	1980
	B.Fisher, R.Ulrich [11] (Germany)	1980
	L.Kaihola [12] (Finland)	1981
	T.Hidaka, T.Morikawa, J.Shimada [13] (Japan)	1981
	T.Hidaka [14] (Japan)	1982

	H.Nakazawa [15] (Japan) 1983
	V.Vinogradov, I.Kozhevnikov [16] (USSR) 1984
	M.Watanabe, I.Suzuki, T.Hidaka et al [17](Japan) 1985
	N.Basov, Yu.Bykovsky, V.Vinogradov, V.Kantsyrev [18] (USSR) 1985
	A.Rindby [19] (Sweden) 1986
	V.Arkad'ev, M.Kumakhov [20] (USSR) 1986
	O.Ananyin, Yu.Bykovsky, A.Zverkov, I.Frondzey [21] (USSR) 1987
	V.Arkad'ev, A.Kolomiitsev, M.Kumakhov et al [22] (USSR) 1987
	N.Geglio, A.Hawryluk, M.Kuhne et al [23] (USA, Germany) 1988
	E.Stern, Z.Kalman, A.Lewis et al [24] (Israel) 1988
	V.Arkad'ev, M.Kumakhov, R.Fayazov [25] (USSR) 1988
	P.Engstrom, S.Larsson, A.Rindby [26] (Sweden) 1989
	D.Thiel, E.Stern, D.Bilderback, A.Lewis [27] (USA) 1989
6.The Certif. of Authorship (USSR) for construction of multicapillary x-Ray concentrator.	M.Kumakhov [28] (USSR) 1984
7.The first multicapillary glass - capillary concentrators for spectral region 1 - 10 keV (type „ point source - point focus'').	V.Arkad'ev, A.Kolomiitsev, M.Kumakhov, I.Ponomarev, I.Knodeev, Yu.Chertov, I.Shakhparonov. [29] (USSR) 1989
	O.Ananyin, Yu.Bykovsky, A.Zhuravlev, V.Znamensky, V.Kantsyrev, S.Frolov. [30] (USSR) 1990
	V.Kantsyrev, A.Kologrivov, K.Kopytok, A.Shlyaptseva. [31] (USSR) 1991
8. The applications of glass-capillary concentrators with table-top plasma source of SXR for solid state physics (type „ point source - point focus", $q_{SXR} \approx 10^6$ W /cm^2).	V.Kantsyrev, A.Kologrivov, K.Kopitok, 0.Ananyin, Yu.Bykovsky, A.Zyabnev, S.Kraevsky,A.Shlyaptseva[32,33](USSR) 1991

9.The application of glass - capillary concentrator for x-ray lithography (type „point source - beam").	W.Gybson, M.Kumakhov, V.Vartanian, R.Youngman, D.Gybson, J.Drumheller, R.Frenkel [34,35](USA, Russia) 1992
10.The application of glass - capillary concentrator for guiding and focusing of neutron beam (type "beam - point source").	H.Chen, O.Xiao,D.F.R. Mildner, V.Sharov, R.Downing [36,37](USA, Russia) 1992
11.The application of glass - capillary converter (GCC) for x-ray imaging diagnostics of hot plasma (type "point source-point focus"', "beam - line focus")	V.Kantsyrev, K.Kopytok, O.Petrukhin, A.Shlyaptseva, A.Faenov, S.Pikuz, N.Mingaliev, W.Romanova, T.Shelkovenko [38,39] (Russia) 1993
12.The application of glass-capillary concentrator for x-ray diffraction measurements (type ''point source - beam'').	V.Kovantsev, J.Pant, V.Pantojas, N.Nazaryan, T.Hayes, P.Persans [40] (USA, Russia) 1993
13.The policapillary monolitic glass capillary concentrator for microfocus application.	S.Hoffman, J.Ulrich, D.Thiel, D.Bilderback, I.Ponomarev, M.Gubarev, N.Gao, Q.Xiao, W.Gibson [41,42] (USA) 1994
14.The theoretical and experimental study of channeling of EUV by single capillariy and test single tapered capillary for photoemission spectromicroscopy.	J.E.Rowe, N.V.Smith, W.A. Royer, R.A. Malic, E.E.Chaban, R.J.Chichester. C.-M.Chiang [43,44] (USA) 1994-1995
15.The test of GCC in EUV spectral region, first application of GCC for EUV spectrometry of week source (type „beam - line focus'').	V.Kantsrev, R.Bruch, M.Bailey, A.Shlyaptseva. [45] (Russia, USA) 1994-1995
16.The test of GCC for measurements of polarization of EUV radiation (λ= 304 A) and patent application, fieled March 30, 1996.	V.Kantsyrev, R.Bruch, A.Shlyaptseva, [46] (USA, Russia). 1994-1996
17.The first application of GCC in far EUV spectral region ($\lambda \leq 1000$ A) for EUV spectrometry of ion - atom collisions (type „ line source - line focus'').	V.Kantsyrev, R.Bruch, R.Phaneuf, V.Golovkina, A.Shlyaptseva, I.Golovkin [47, 48] (USA, Russia). 1995-1996

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