The two pulses two wavelength EUV radiation LPP source and 4M Bragg mirror lens for laboratory EUV Lithography tool:
Development of the ISTC project #3857

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ISTC project # 3857

“Key Technologies of EUV-nanolithography System of Super high Resolution on the Base of High Effective LPP Source”

February 2009 – February 2012

Project Budget – 317,501 € = $492,700

executors:

Ioffe Institute

and

Institute for Laser Physics,

both Saint-Petersburg, Russia

Collaborators of the Project

1. Gerry O’Sullivan,
2. John Costello,
3. Torsten Feigl,
4. Peter Choi,
5. Ladislav Pina,

all COST MP0601 participants

ISTC project #3857,

Second year Work Plan

1. Design of dual-wavelength (λ = 1.06 μm and λ = 10.6 μm) laser- optical scheme forming focal spot on the target at double-pulse illumination.

2. Testing of the key elements of dual-wavelength double pulse illumination laser system

3. Design and manufacturing parts of the 4-mirror wide-aperture objective.

4. Manufacturing and testing of the auxiliary NL elements

Outline

- **Design of dual-wavelength (DW) double-pulse (DP) laser-optical scheme**
- Idea and up-to-date DWDP LPP systems
- Development of DWDP LPP system in the Project
- Technology of laser pulse compression
- Inert buffer gas effect on the SCS
- The SCS 1.90…1.96 μm => 9.1…10.6 μm conversion in multipass cavity
- Experimental testing of proposed DWDP LPP system
- **Powerful CO_2 amplifier**
- Low frequency and high frequency (slab) CO2 lasers
- Intercascade nodes in YAG:Nd master-oscillator - CO_2 amplifier scheme.
- The objective focusing laser radiation onto the target.
- **4-mirror wide-aperture imaging objective**
- Design of 4M imaging lens
- Installation of 4M lens into 2M NL housing
- Improvement of technology of aspheric optical elements
- Bragg mirror technology optimization for the mask
- Multilayer transmitting EUV filters.

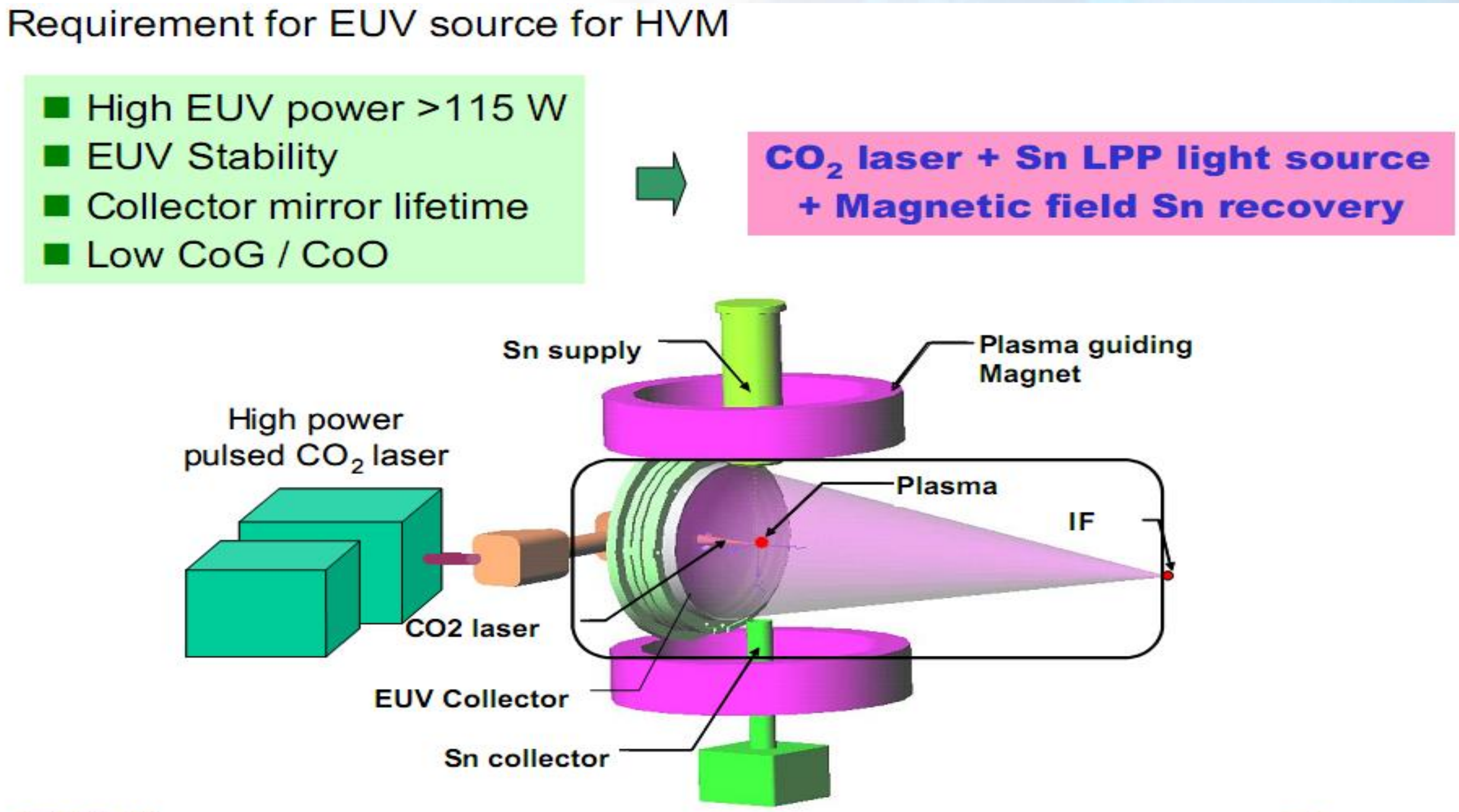
Design of dual-wavelength (DW) double-pulse (DP) laser-optical scheme

Idea and up-to-date DWDP LPP systems

The idea of two pulse and two color LPP seems belongs to our colleague Alex Andreev.
Andreev A.A. et al., Proceeding of SPIE, v.4343 p.789 (2001).
Andreev A.A., Nikolaev V.G., Platonov K. Yu., Kurakin Yu. A. ZhTF, V.77, #.6, p.62 (2007).

Well known realization you can see, for example, in presentations of SEMATECH symposium 2008. The realization was described, for example, by Akira Endo et al. in symposium Tahoe 2008

Typical industrial EUV LPP source (by Akira Endo et al)



Advanced LPP source for NL tool
(by A. Endo)

1. EUV source power of 500 – 1000 W / 2π can be obtained in double pulse irradiation scheme with a tin droplet target and 13 – 20 kW CO_2 main pulse.

2. Conversion efficiency of > 4% has been experimentally achieved from a Sn droplet with 36 μm in diameter with the two-color laser, double pulse irradiation scheme.

3. We have also discussed advantages of the scheme, such as reduction of high energy ions, ion mitigation by B-field, and Sn cleaning by hydrogen radicals.

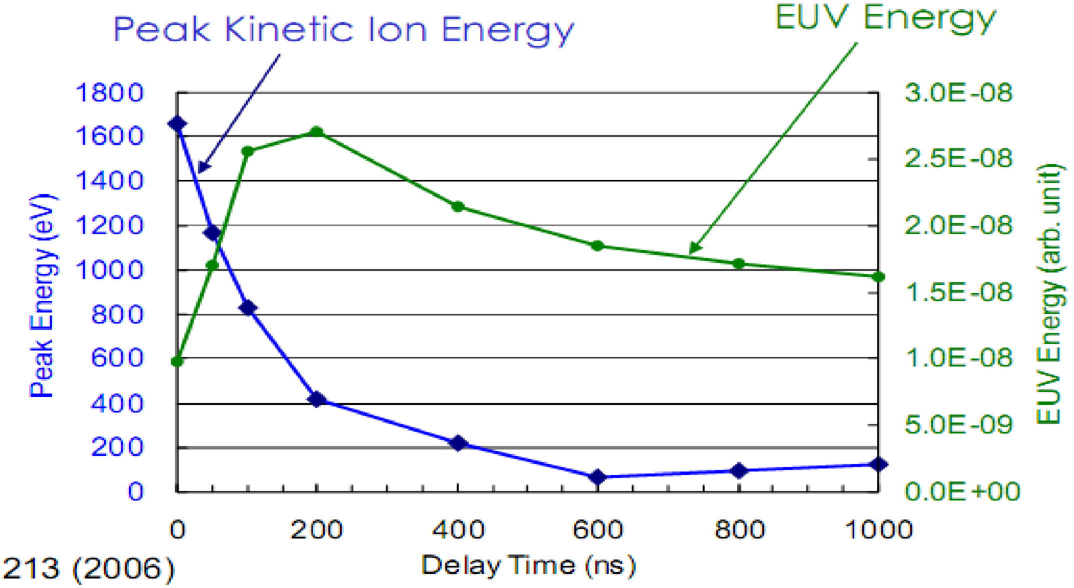
Optimal delay time for Sn plasma

Ion Energy measurement:

- ✓ Time of Flight Method (TOF)

Laser Energy

- ✓ Pre-Pulse (Nd:YAG Laser): 5mJ
- ✓ Main-Pulse(CO_2 Laser): 65mJ



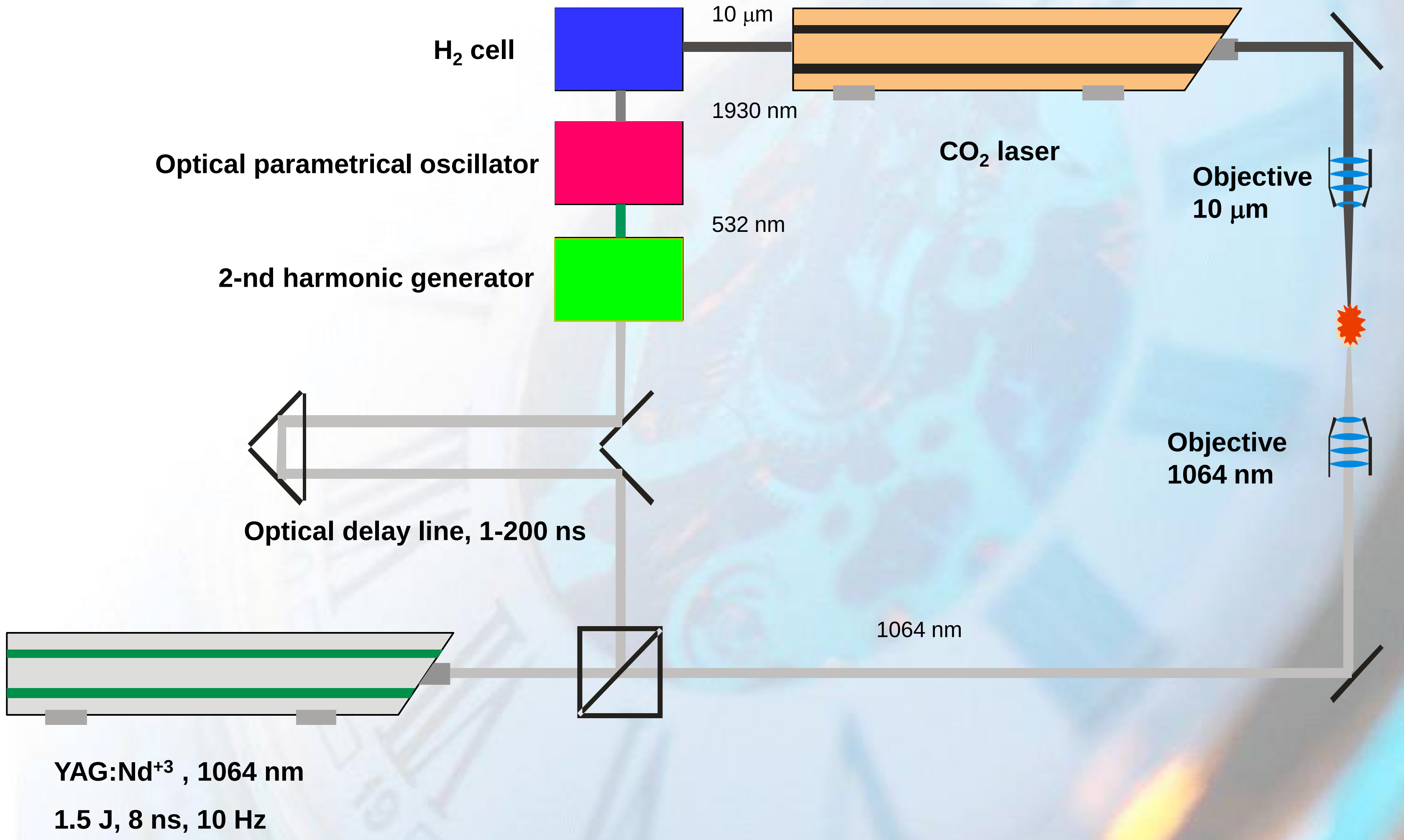
Ref: Appl. Phys. B 83, 213 (2006)

The peak ion kinetic energy decreases with delay time for the CO2 laser irradiation.
0.5 T magnetic field can fully control tin ions.

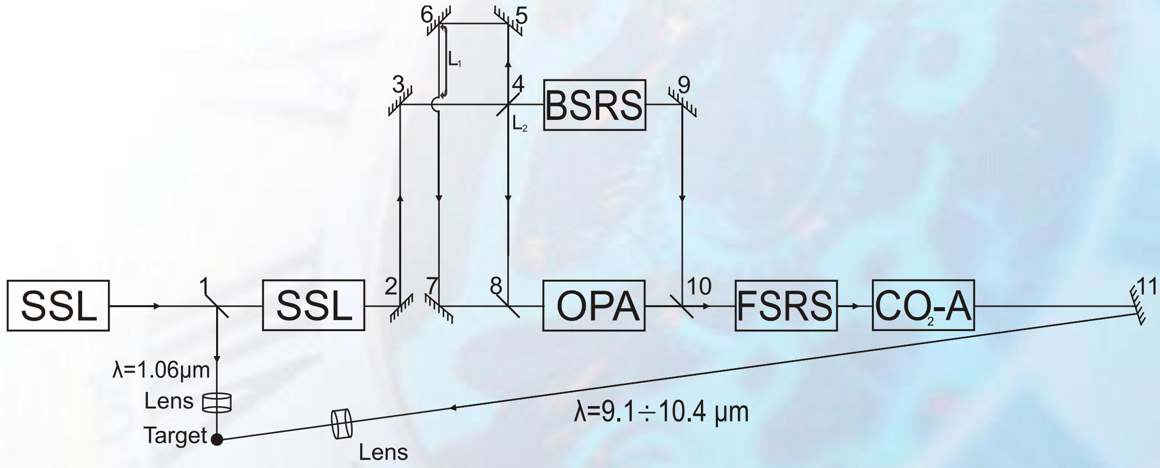
The main ideas of the industrial EUV LPP source

- The main ideas used in the SYMER source (as well as in GIGAPHOTON source) are the following.
- Target material should be Sn (liquid Sn droplets)
- The main primary laser should be pulsed powerful (about 15-20kW) CO2 laser
- The main ways to solve debris mitigation problem are the use of magnetic field and
- The use of inert gas curtain

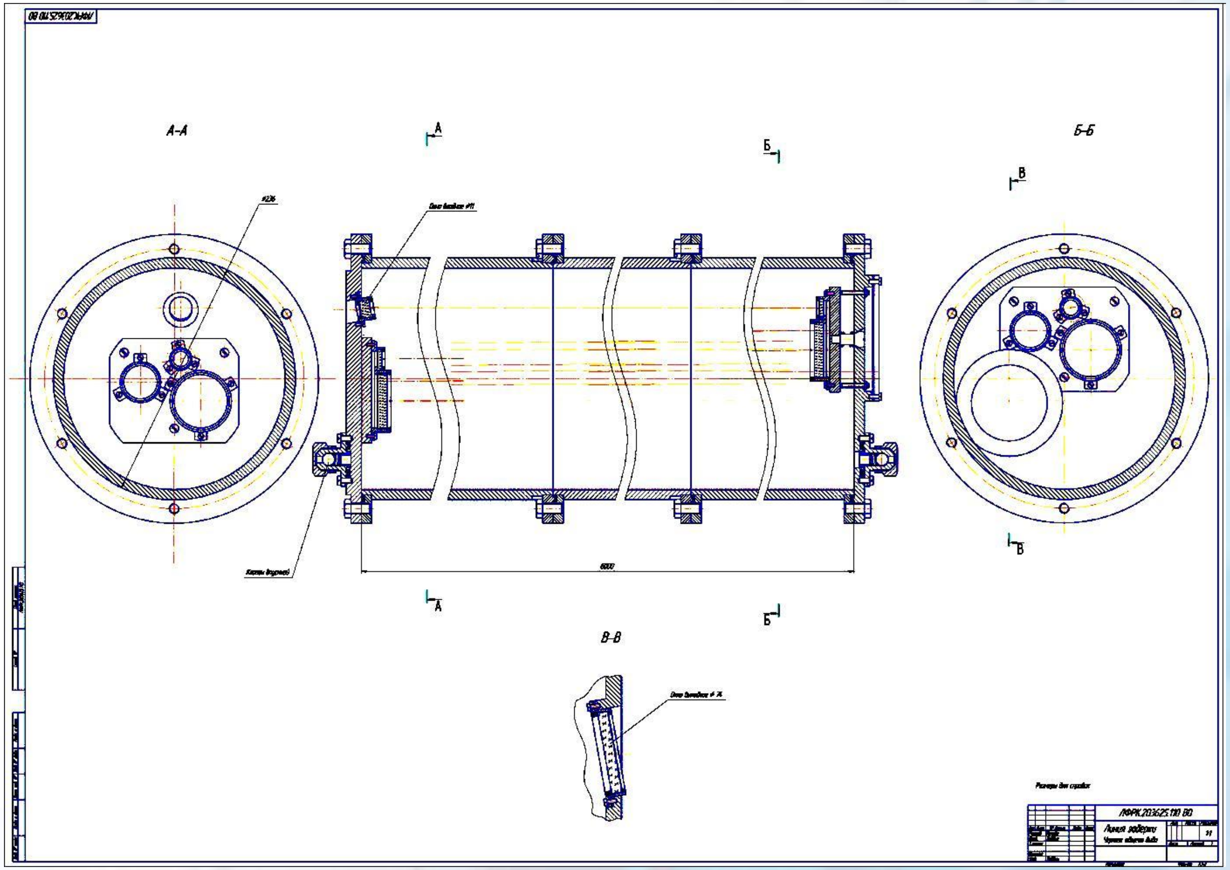
Former design of dual-wavelength (λ = 1.06 μm and λ = 10.6 μm) laser-optical scheme forming focal spot on the target at double-pulse illumination (Dresden 2008)



Resulting dual-wavelength (λ = 1.06 μm and λ = 10.6 μm) laser-optical scheme forming focal spot on the target at double-pulse illumination (simplified). Patent of RF 16.05.11

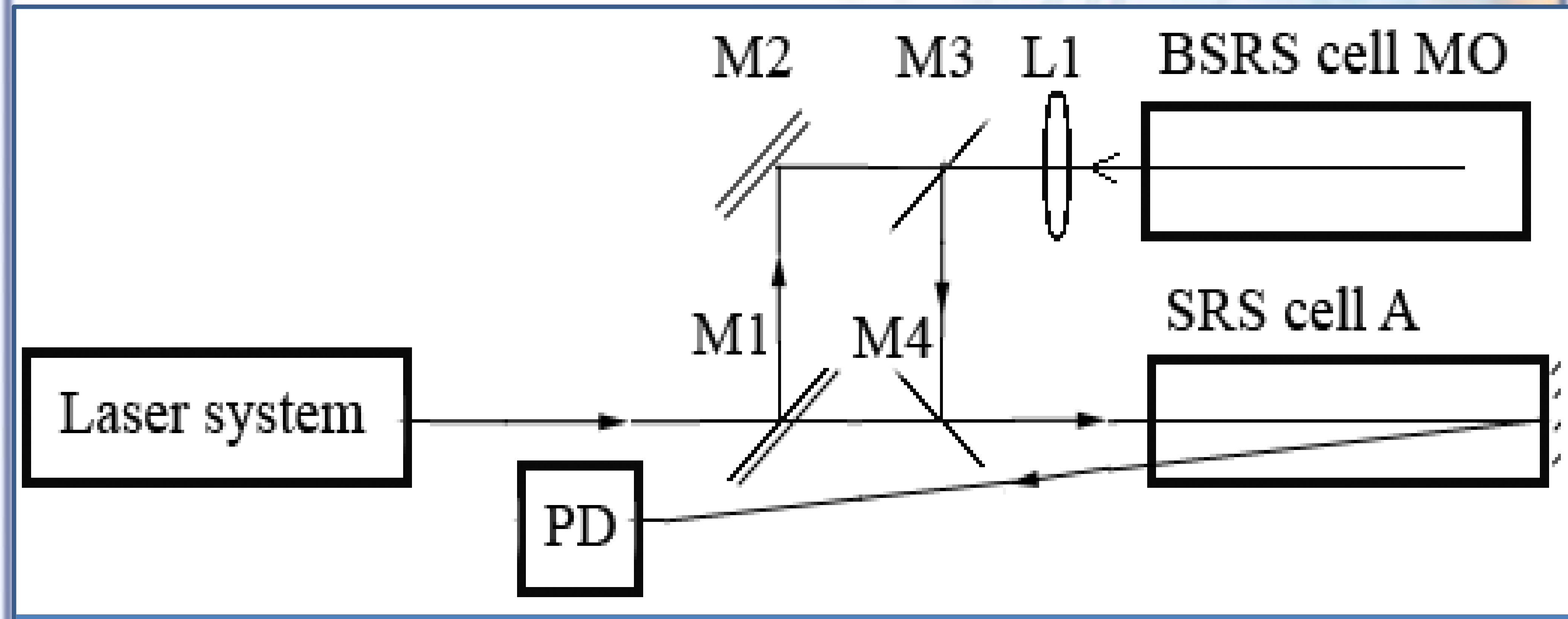


The SCS 1.90…1.96 μm => 9.1…10.6 μm conversion in multipass cavity and simultaneously delay time line – up to 200 ns.



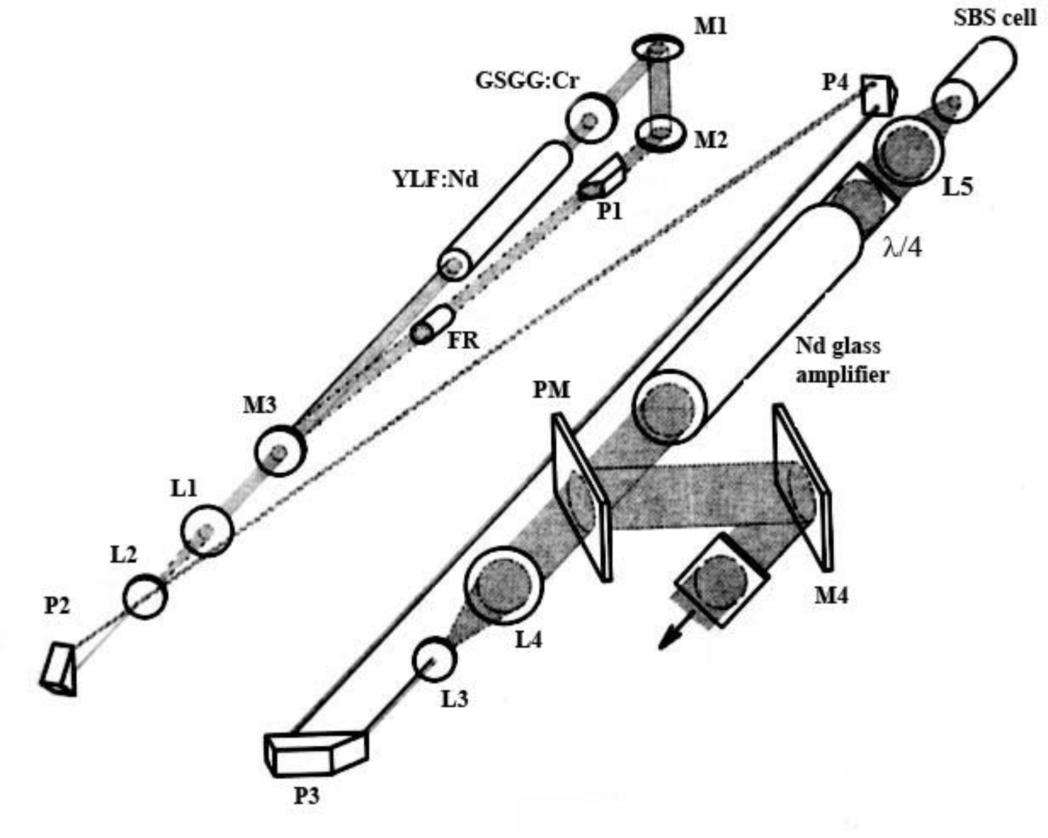
Multipass cavity for laser beam conversion

The cavity is filled up by a mixture of hydrogen, nitrogen, helium. Maximum mixture pressure is of 150 atm. There are two sets of different mirrors at the top and at the bottom of cavity (total length 6000 mm).



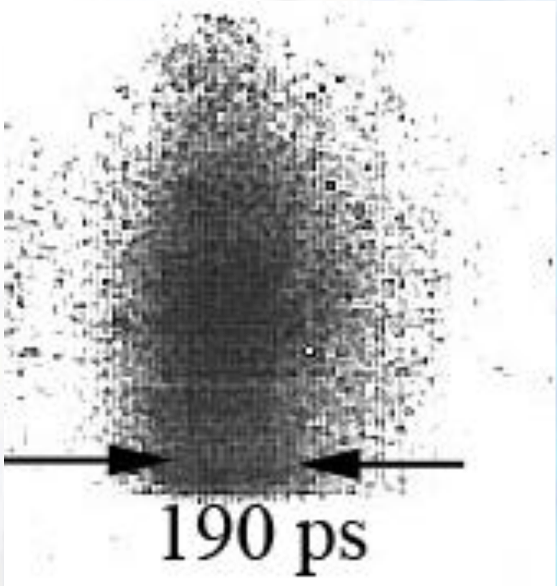
Experimental setup for LS testing

. Block diagram of experimental setup: M1 - dielectric mirror with $R_{\square = 528nm}$= 20% at the angle of 45□; M2 - dielectric mirror with c $R_{\square = 528\ nm}$ □ 100% at the angle of 45□; M3, M4 - dielectric mirrors with $R_{\square = 528\ нм}$ □ 0% and $R_{\square = 680\ нм}$ □ 100% at the angle of 45□; L1 – lens with f = 100cm ; BSRS cell MO – SRS cell of the backward Stokes radiation (master oscillator); SRS cell A – SRS cell of two-pass amplification; PD – energy meter



Block diagram of the next experimental setup

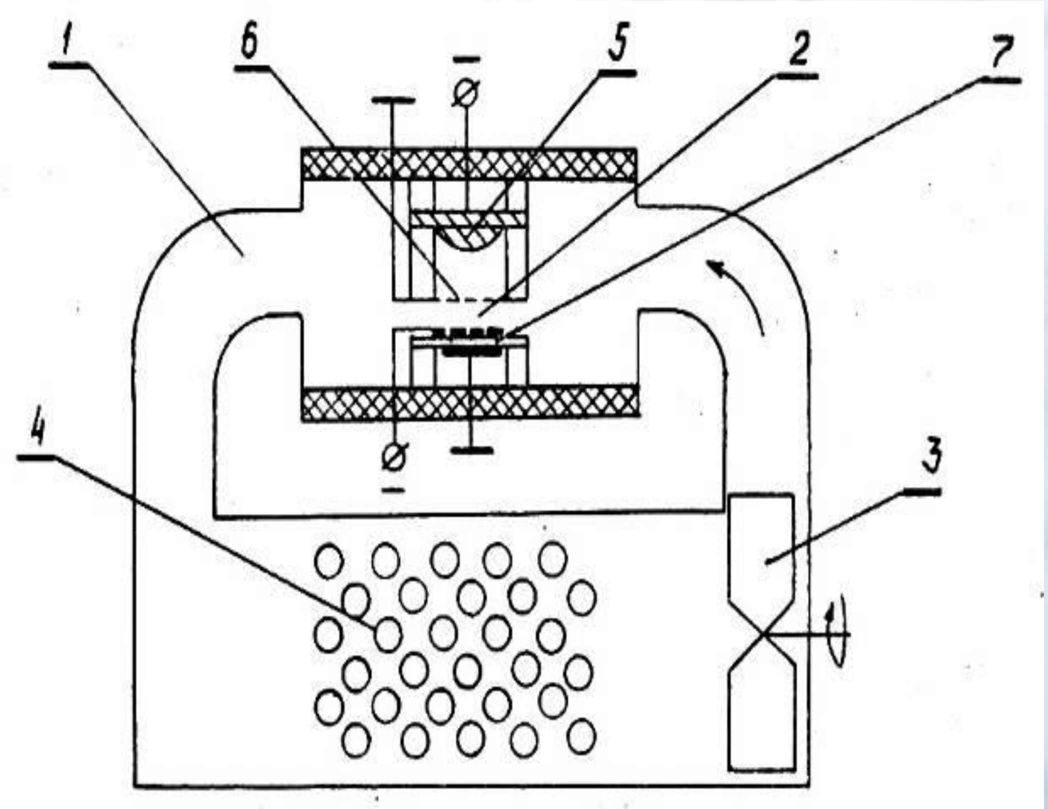
M1 - dielectric mirror with $R_{\square = 528nm}$= 20% at the angle of 45□; M2 - dielectric mirror with c $R_{\square = 528\ nm}$ □ 100% at the angle of 45□; M3, M4 - dielectric mirrors with $R_{\square = 528\ нм}$ □ 0% and $R_{\square = 680\ нм}$ □ 100% at the angle of 45□; L1 – lens with f = 100cm ; BSRS cell MO – SRS cell of the backward Stokes radiation (master oscillator); SRS cell A – SRS cell of two-pass amplification; PD – energy meter

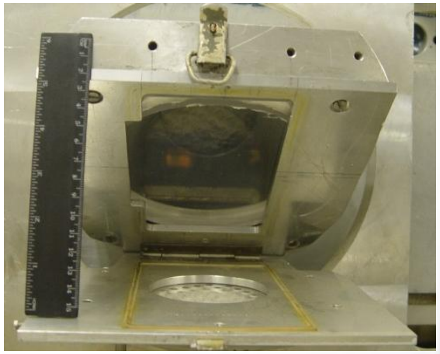


A laser pulse photo chronogram.

Laser pulse compression

Powerful CO_2 laser “Fialka” was used as a model of the final amplifier.



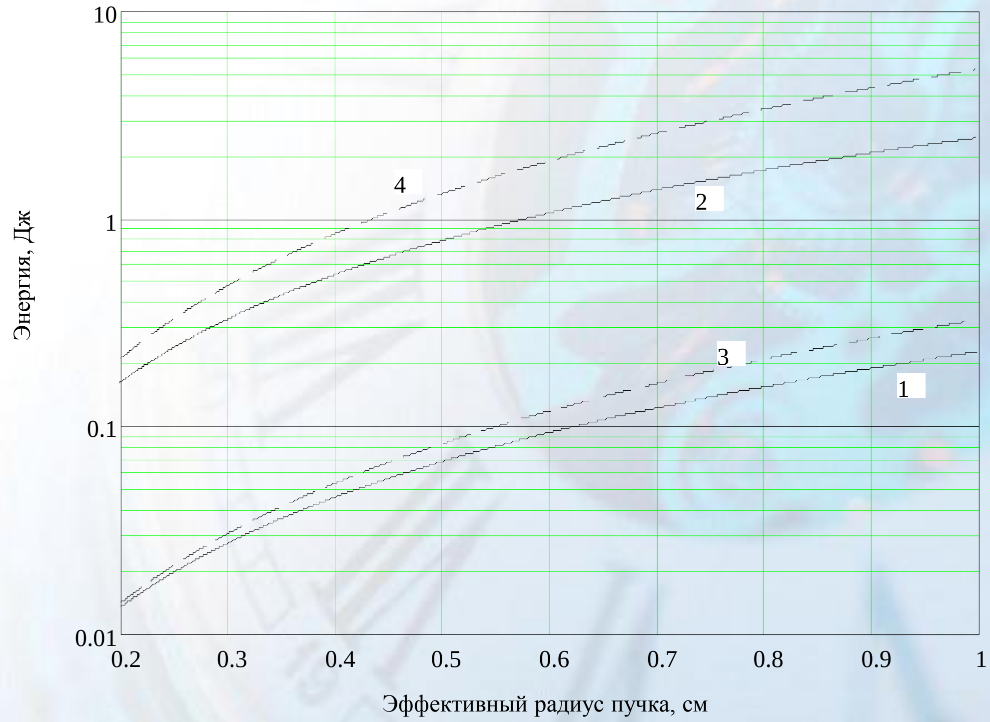


Powerful CO_2 low frequency laser (FIALKA)

discharge current duration	1-1.5 μs
pulse repetition rate	25-50 s^{-1}
stored energy at excited level	4 J

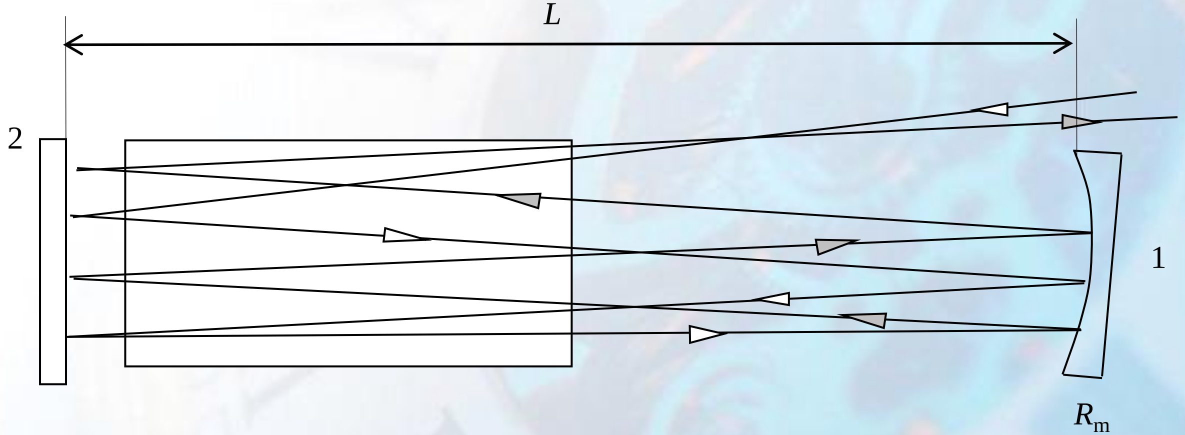
Calculation of CO2 laser driver using “Fialka”

Possible amplification of 6 pass CO2 laser driver (1ns initial pulse) based on FIALKA



Multipass scheme of CO_2 amplifier

Amplifier based on CO_2 laser “Fialka”



High frequency powerful CO2 laser available for the industrial use

Industrial

Slab-shaped 4000 W CO_2-laser
with RF excitation.

4000 *W CO_2-laser has been designed for integration into laser based processing systems for cutting, drilling, welding or heat treating. The diffusion cooled RF excited Slab-shaped construction allows for a compact, rugged Design, which produces a high quality, round, symmetrical beam. This results in faster cutting speeds with improved edge quality and a minimum heat affected zone.*
Complex tests of pilot model of the laser were today successfully completed.

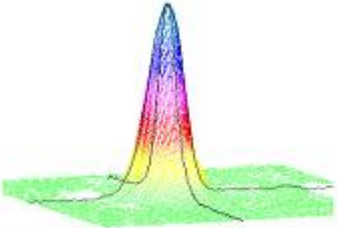
The laser S-4000 on test stand of ILP

Essential features:

- Excitation frequency – 40MHz.
- Laser Head is integrated with Power Supply Unit.
- The divergence of laser radiation is near diffraction limit.

Specification

Average output power:	4000 W
Power range:	200-4000W
Beam quality:	$M^2 \leq 1,2$
Beam diameter:	25mm.
Wavelength:	10,6 μm
Output power stability:	±3% (24 hours)
Polarization:	Linear, 45^0 to base
Pulsed mode	
Frequency:	10 Hz – 10 kHz
Duty cycle:	0~100%
Dimensions (L×W×H):	2070×800×1350mm
Total weight:	1500kg



Far-field pattern of the output radiation.

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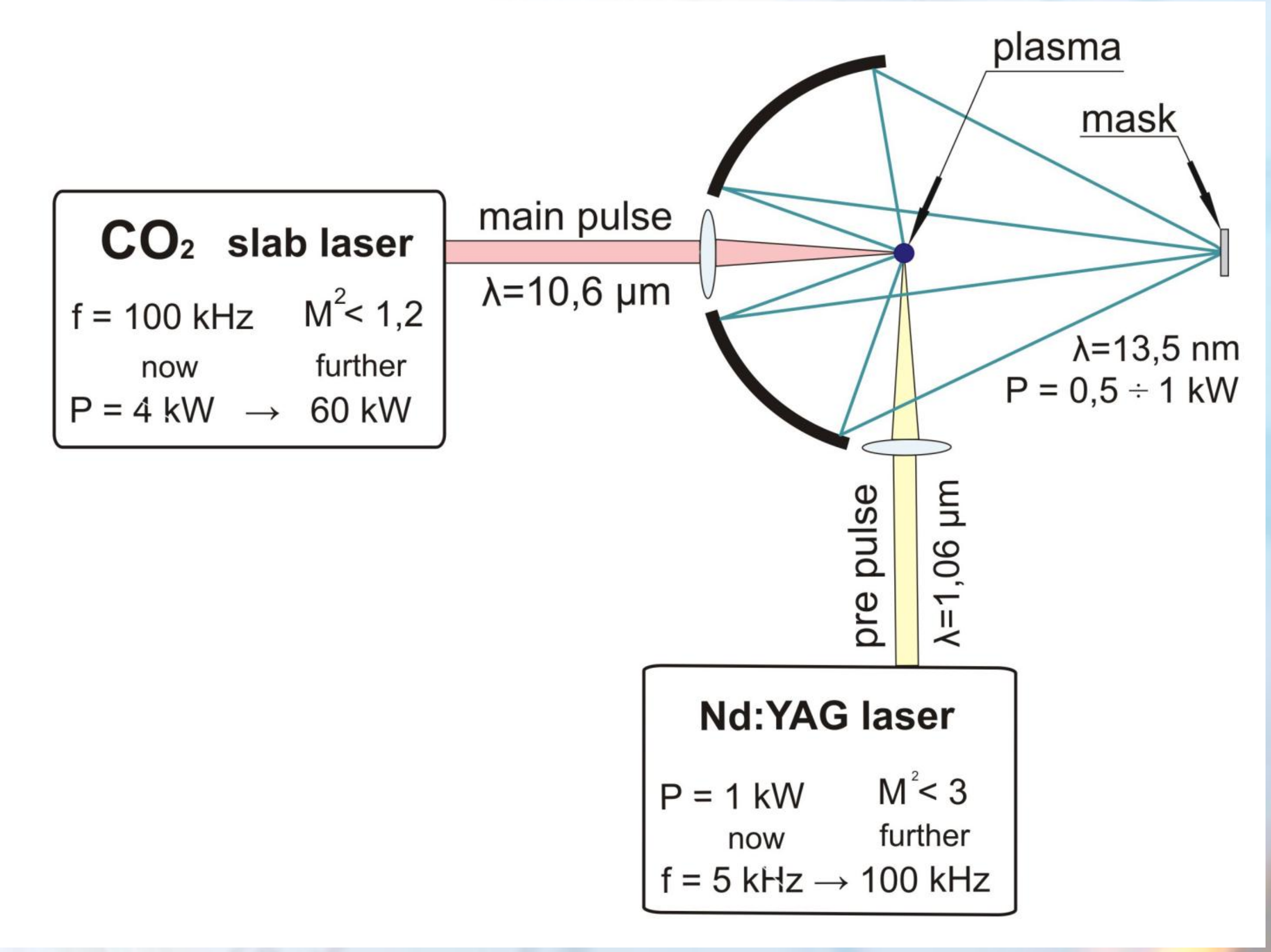
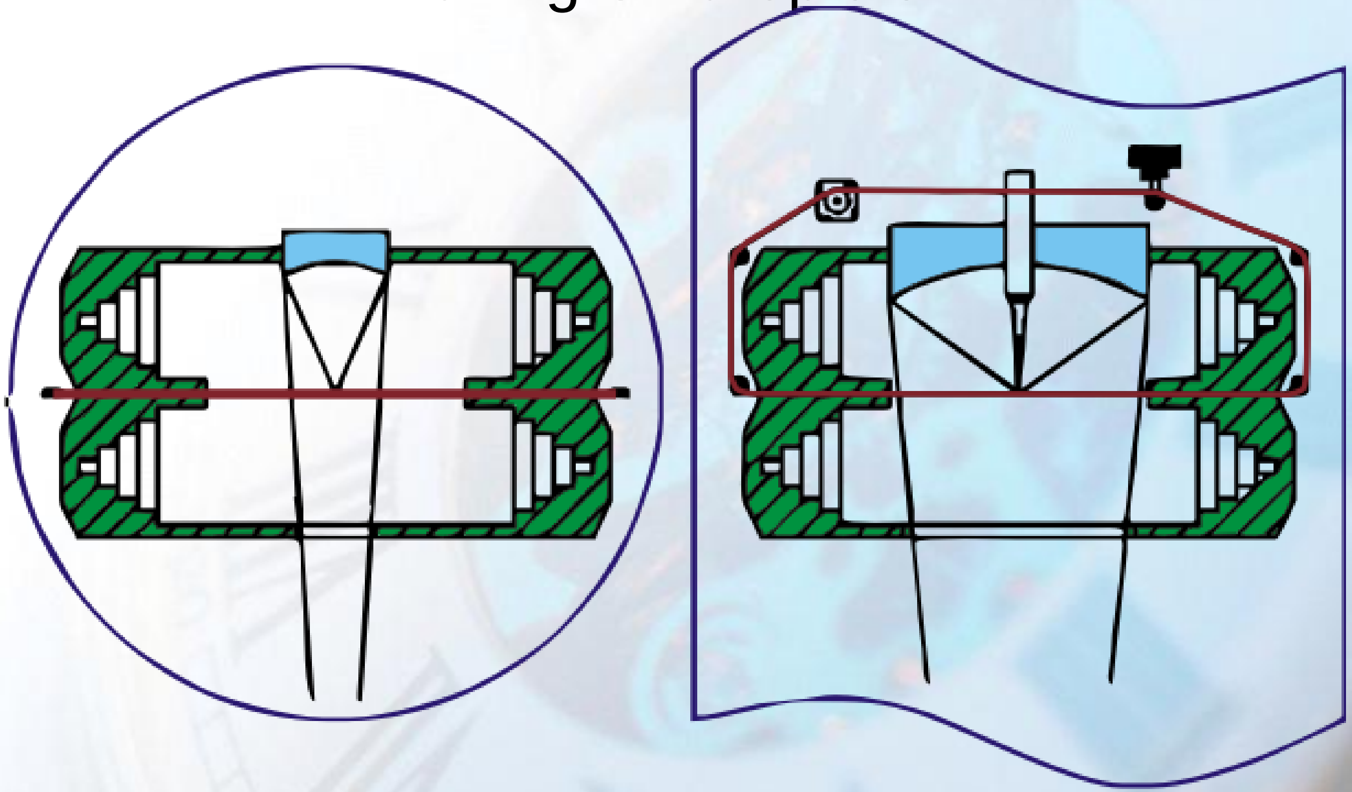
Modern requairements to the industrial LS

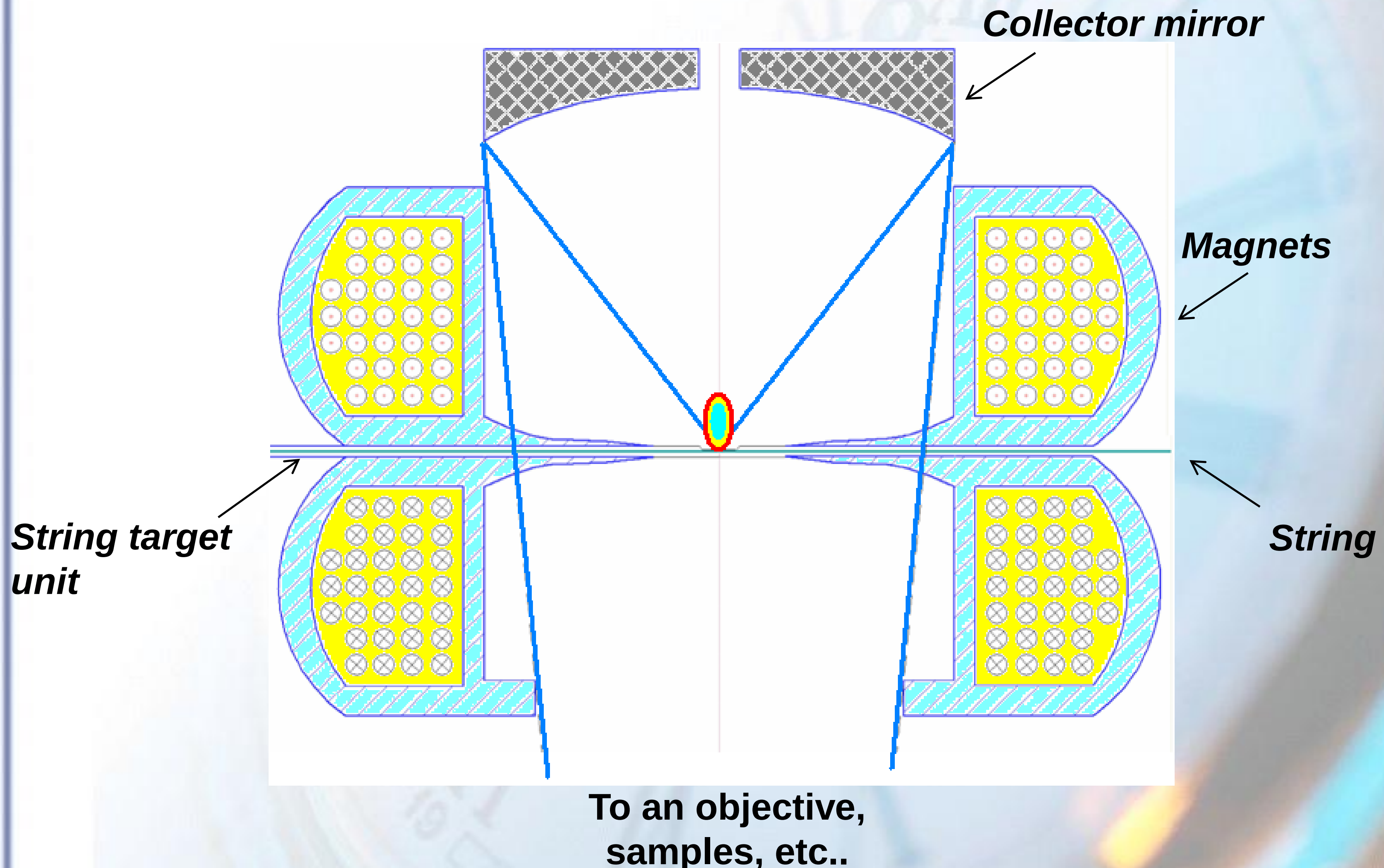


Cross-section of string source.
RF Patent 94003, 27.01.2009

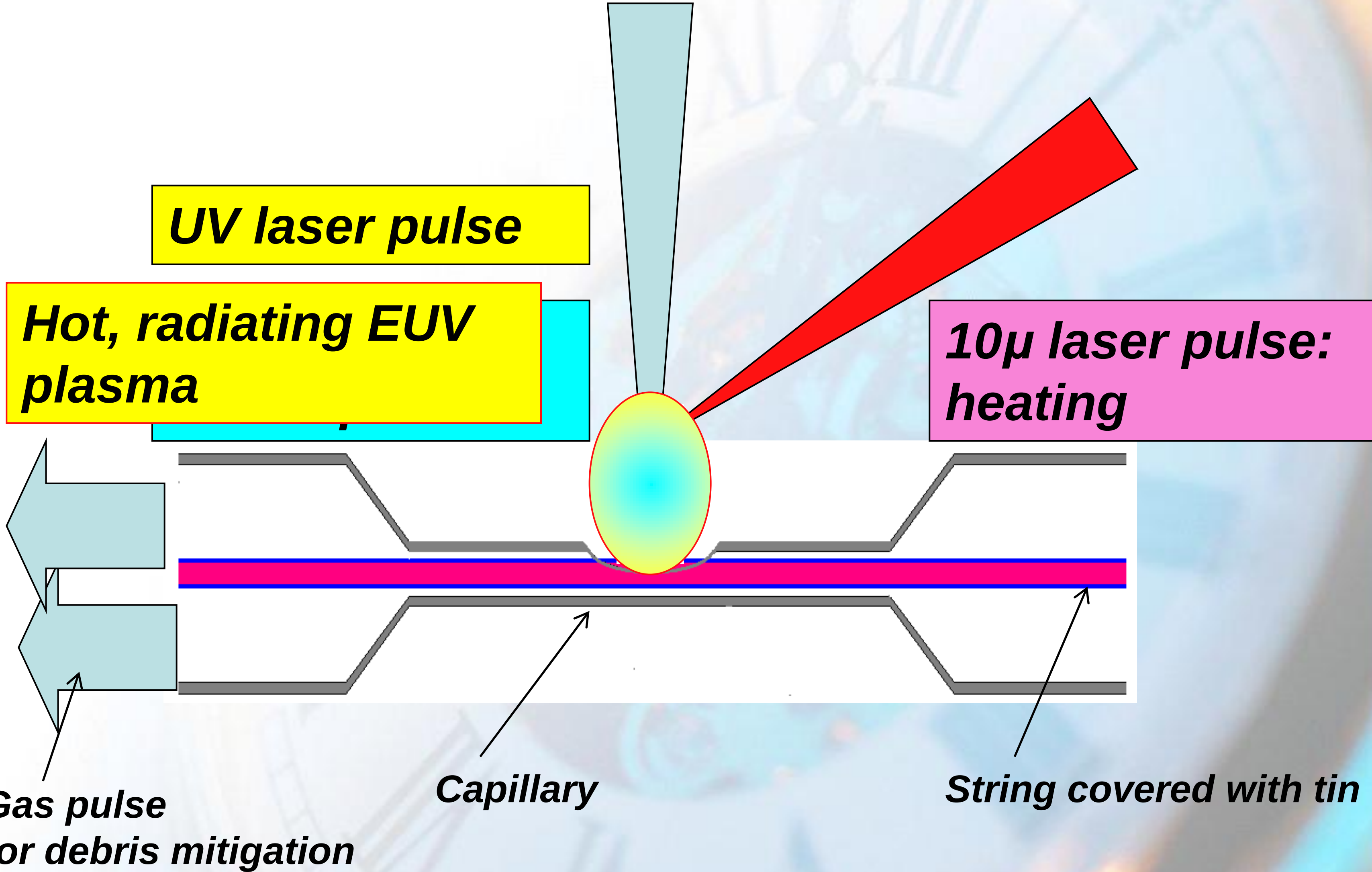
The string source is considered as an alternative to the free falling Sn droplets



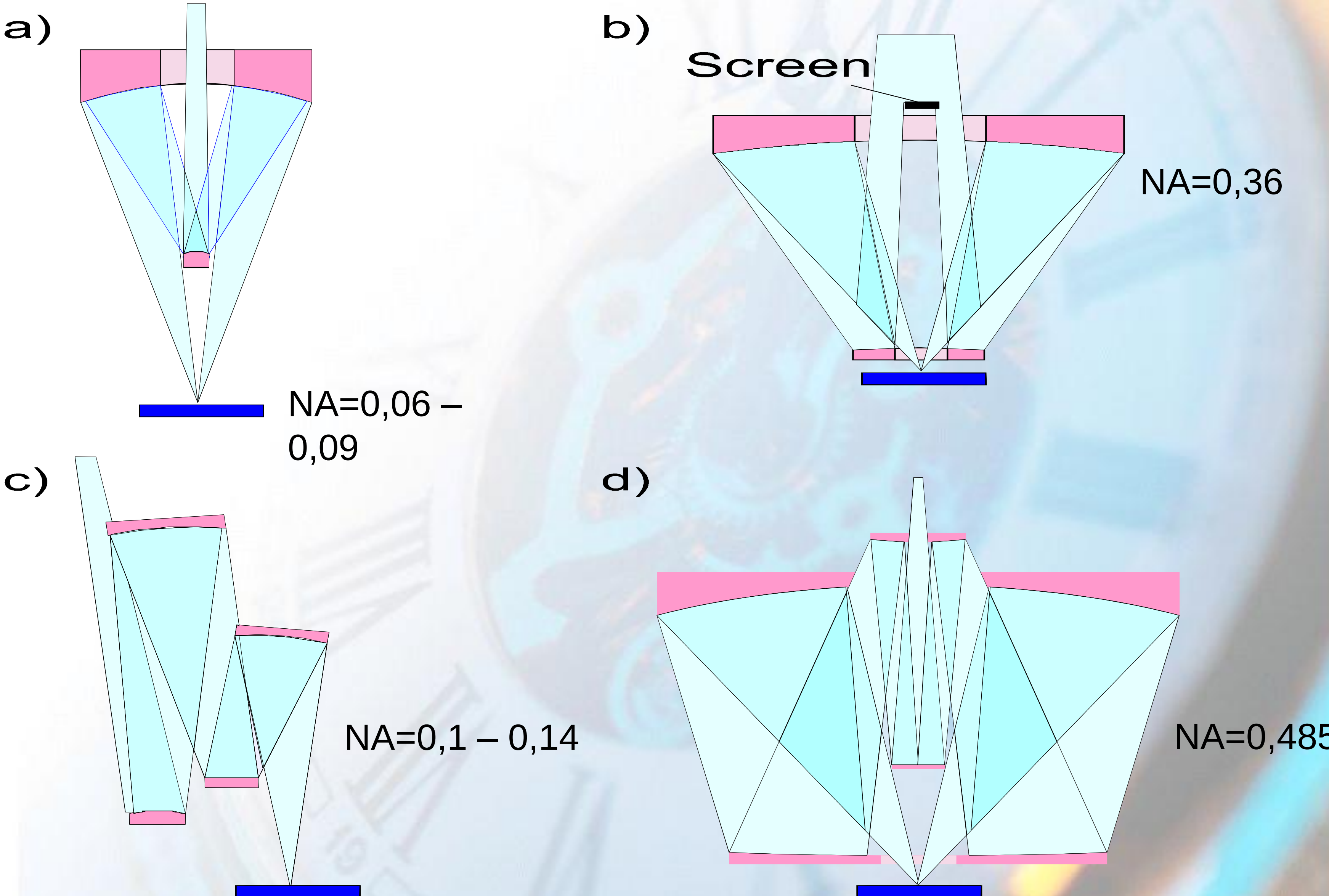
The “String” EUV Source cross-section



“String” EUV target with different laser wavelength ignition and heating



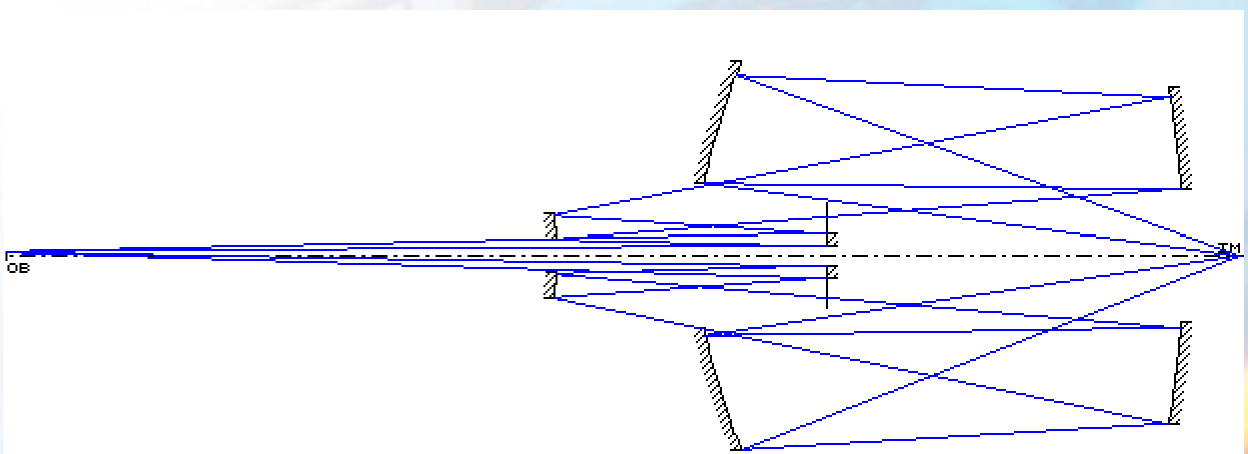
4-mirror wide-aperture imaging objective



4-mirror wide-aperture imaging objective

RF Patent, 93999 09.02.2009.

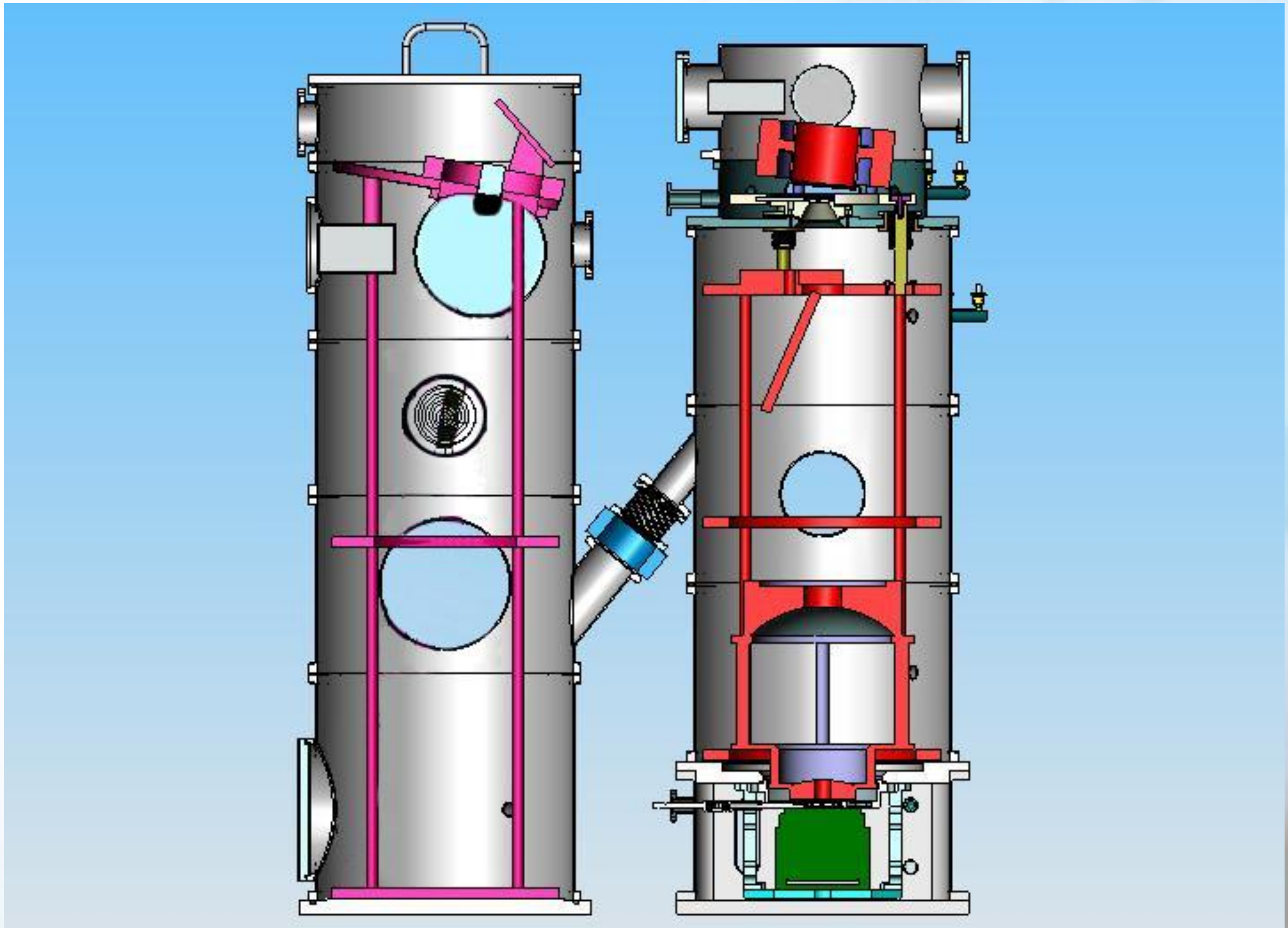
Results of mathematical modeling of microstructures.
The image of corners with width of a line 10 nm in the centre of a field



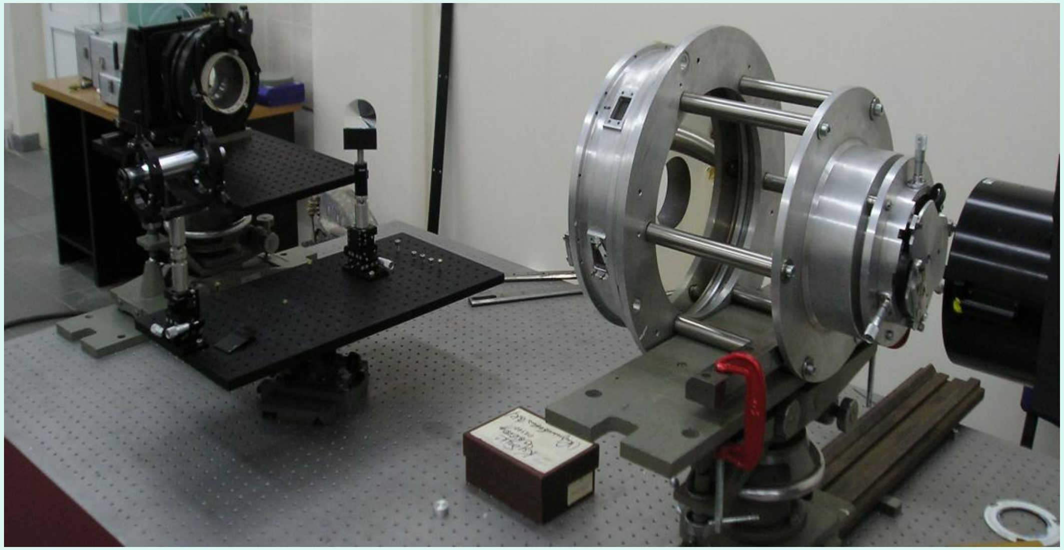
Specification of the objective

The numerical aperture	0.485
The resolution	10 nm with contrast 0.26
	20 nm with contrast 0.35
The sizes of the field of the image	1.2x1.2 $mm^2 \rightarrow 2.0x2.0 mm^2$
The central shielding	0.407
The distance from a mask up to a plane of the image	829 mm
Root mean square wave aberration on the field of the image	0.0573 - 0.1181
The limiting resolution	68000 mm with contrast 0.02
The magnification of the objective	12

New 4M Bragg mirror imaging system with high resolution to minimize expanses should be implanted into the body of existing parts of 2M nanolithogapher

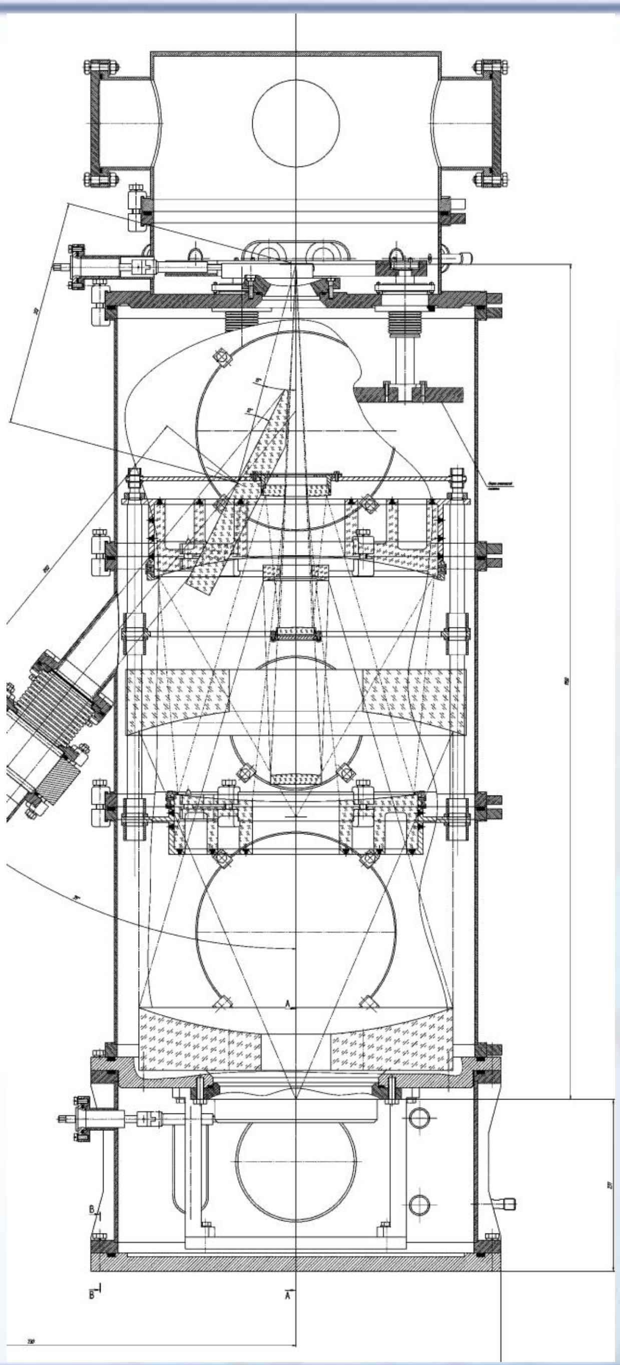


Metrology of EUV objective



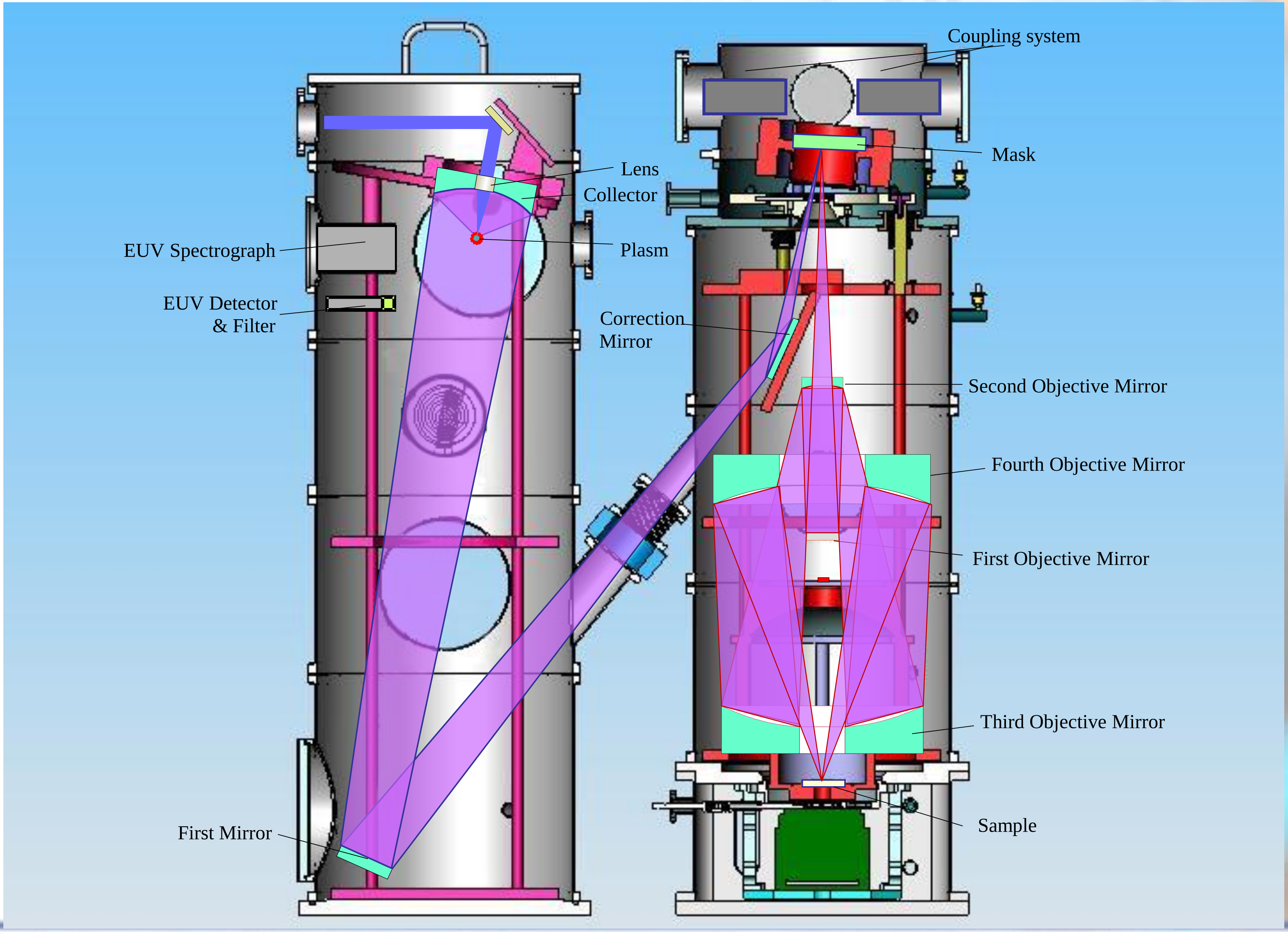
Ioffe Institute Experimental Nanolithographer (2M EN) in course of construction

View of the experimental hall with the dustless room (center and right) intended for EN

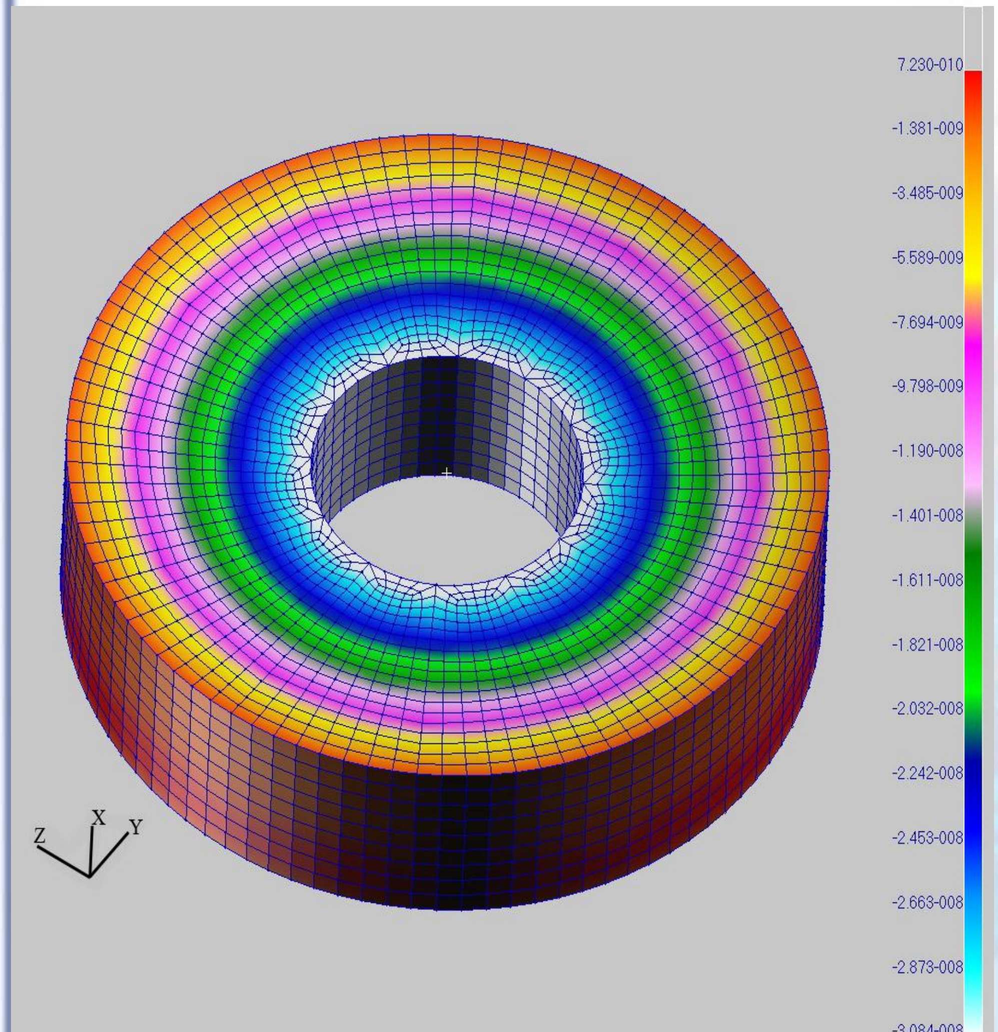


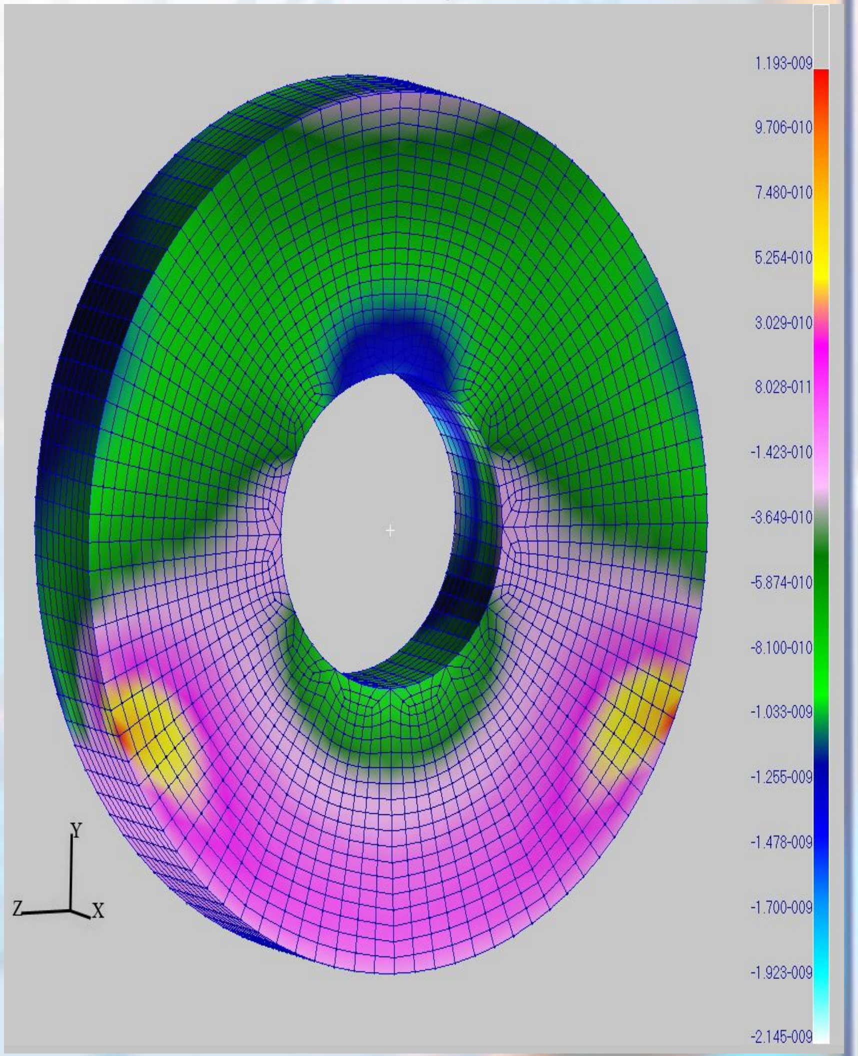
- Variants of the possible installation of 4M lens into the body of 2M EN

Scheme of nanolithographer with 4M lens

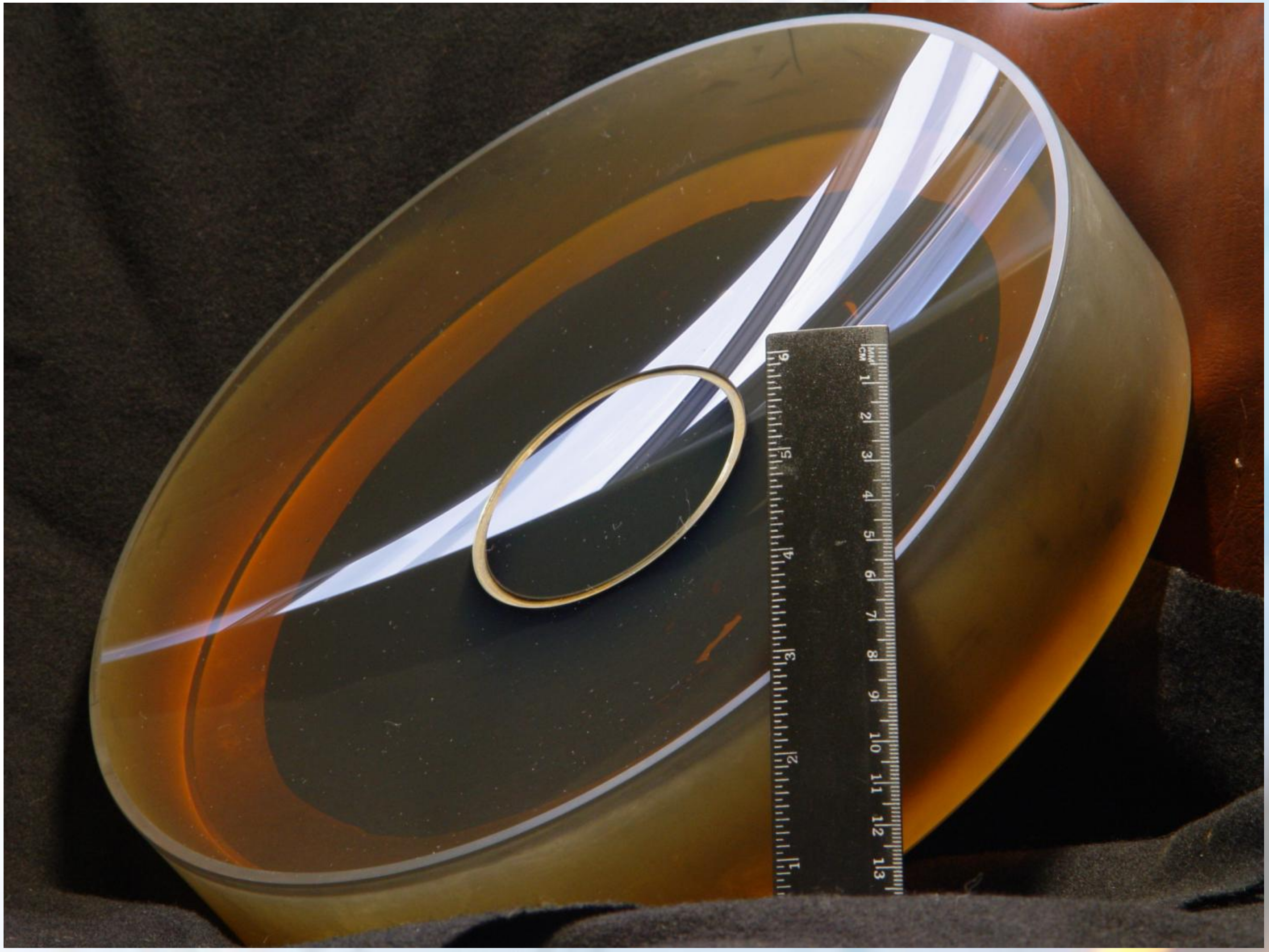


Calculation of mechanical strain distribution on the mirror substrate depending on it’s arrangement in the tool (horizontal and vertical)





Mirror substrate of EUV objective

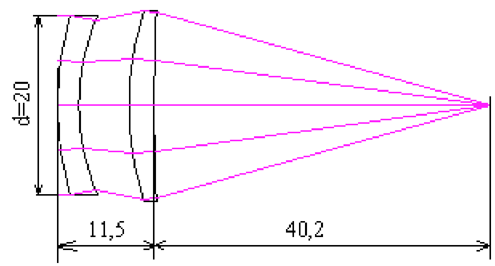


Masks for obtaining of specified aspherical surface profile by ion etching.

Exterior view of intercascade separator

Separators should be used in the master oscillator - CO_2 amplifier scheme for suppressing the self-excitation in the final amplification stage. Separator uses a mixture of SF_6 with *He* (*He* pressure – up to 750 Torr).

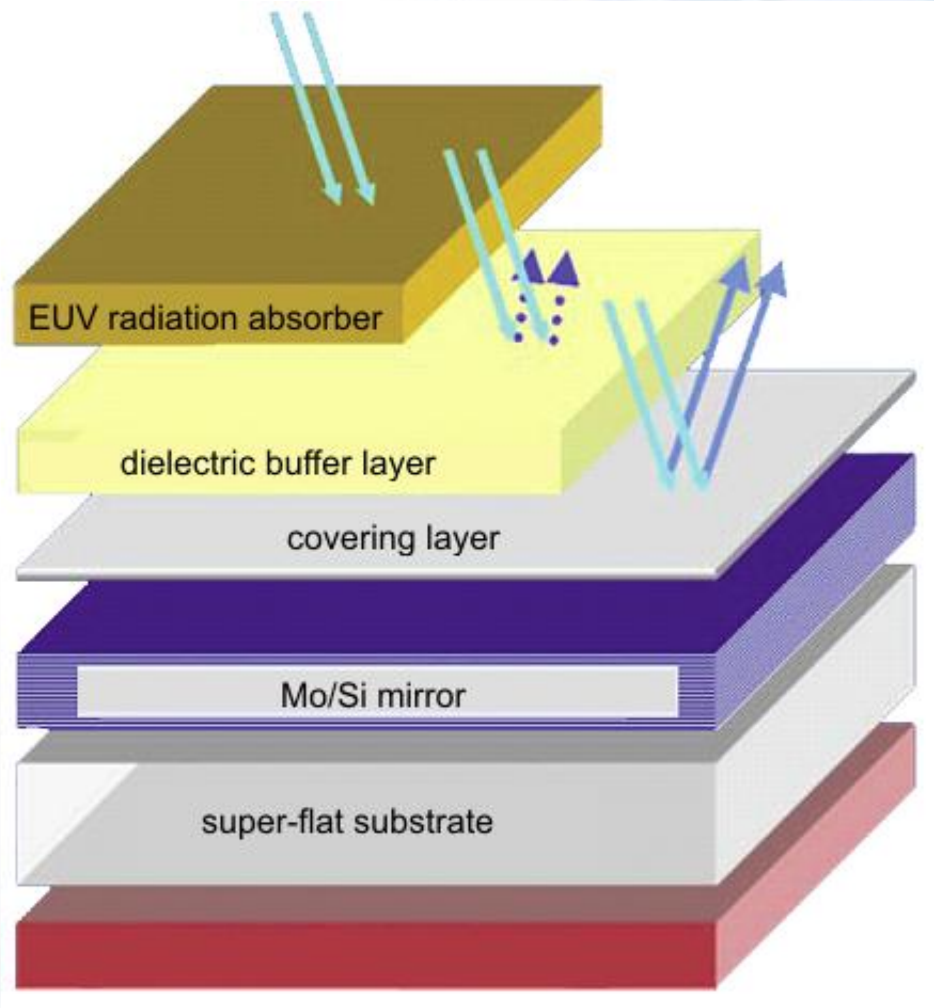
Objective focusing CO2 laser radiation onto the target



№ pos.	Detail name	R(mm)		∅	Arrow on ∅cl.	d(mm)		$n_{\lambda=10,6\ mkm}$	Material
		№	Value			№	Value		
1	Lens	1	33,903	20,0	1,51	1	2,5	2,405531	ZnSe
		2	23,909	20,0	2,19	2	6	1	
2	Lens	3	31,333	21,0	1,81	3	3	2,405531	ZnSe
		4	198,823	21,0	0,28	4	40,223	1	

Objective focusing F'=40 1 : 2 1.5 mrad λ=10,6 mkm

Structure of Reflecting Masks for EUV Lithography



Improvement of technology of processing aspheric optical elements with extreme profile/form accuracy.

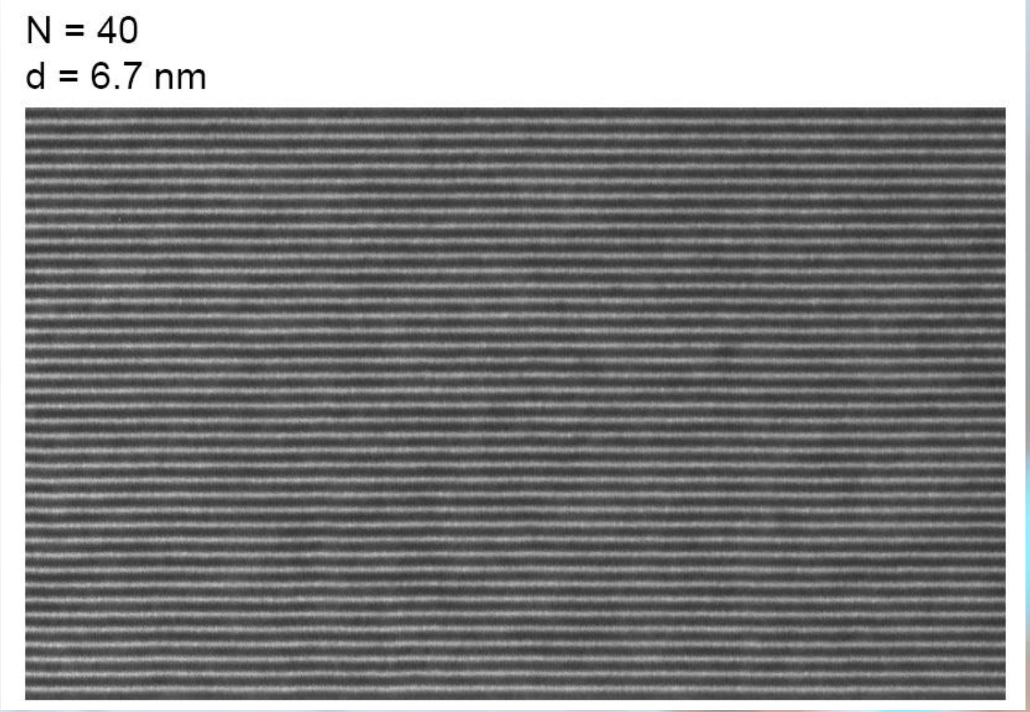
A high-frequency roughness, equal to 0.07 nm - 0.12 nm RMS has been achieved for an amorphous material such as fused silica

Sample number	1	2	3	4	5	6
MSFR, nm	0,3 0,4 0,3 0,2	0,2 0,3 0,5	0,3 0,3 0,3	0,5 0,4 0,3 0,2 0,5	0,2 0,2 0,3 0,2	0,3 0,4 0,3

Multilayer interference coatings used for mask production

R = 70%

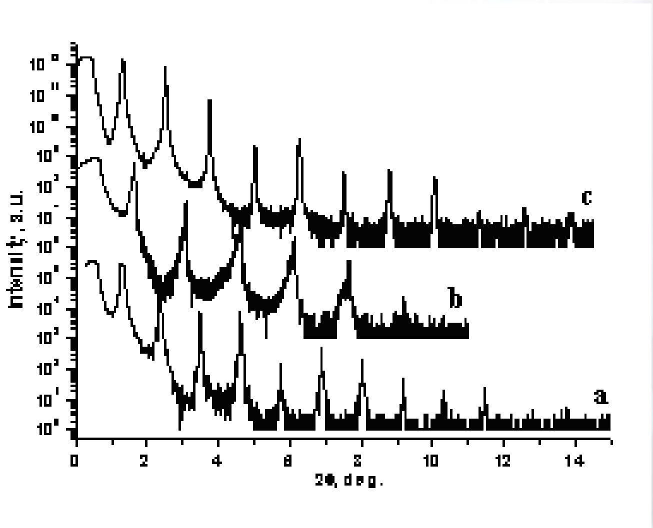
Alternating layer materials with large (Mo, 42, scattering layer) and small (Si, 14, «spacer») atomic numbers.



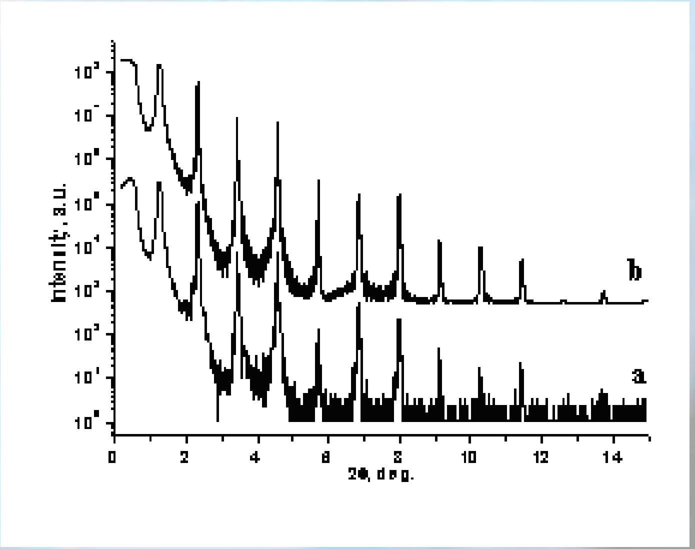
$d = \lambda/2$

X-ray reflectometry (XRR) of the mask MLB mirrors

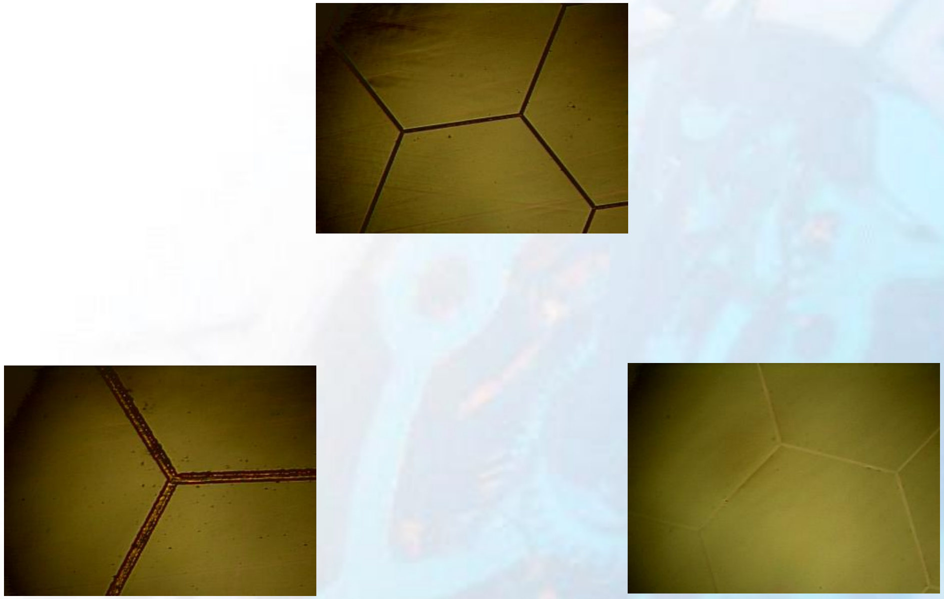
XRR experimental curves для Mo/Si MLS: a – S427, b – S479, c – KK892



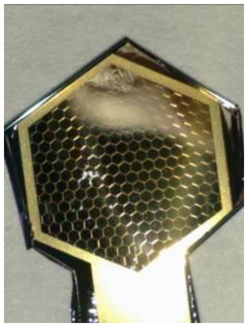
XRR experimental curve (a) and the calculated one (b) for S427

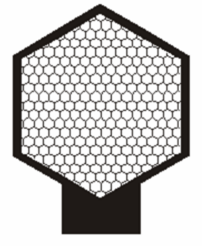


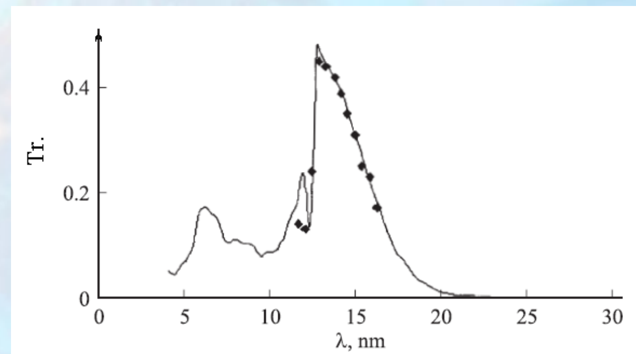
Design and technology of EUV spectral purity filter



Fragments of SPF on the hexagonal mesh manufactured with the use of ML system Zr, Nb/Si , and LOR, Au and Ni mesh.



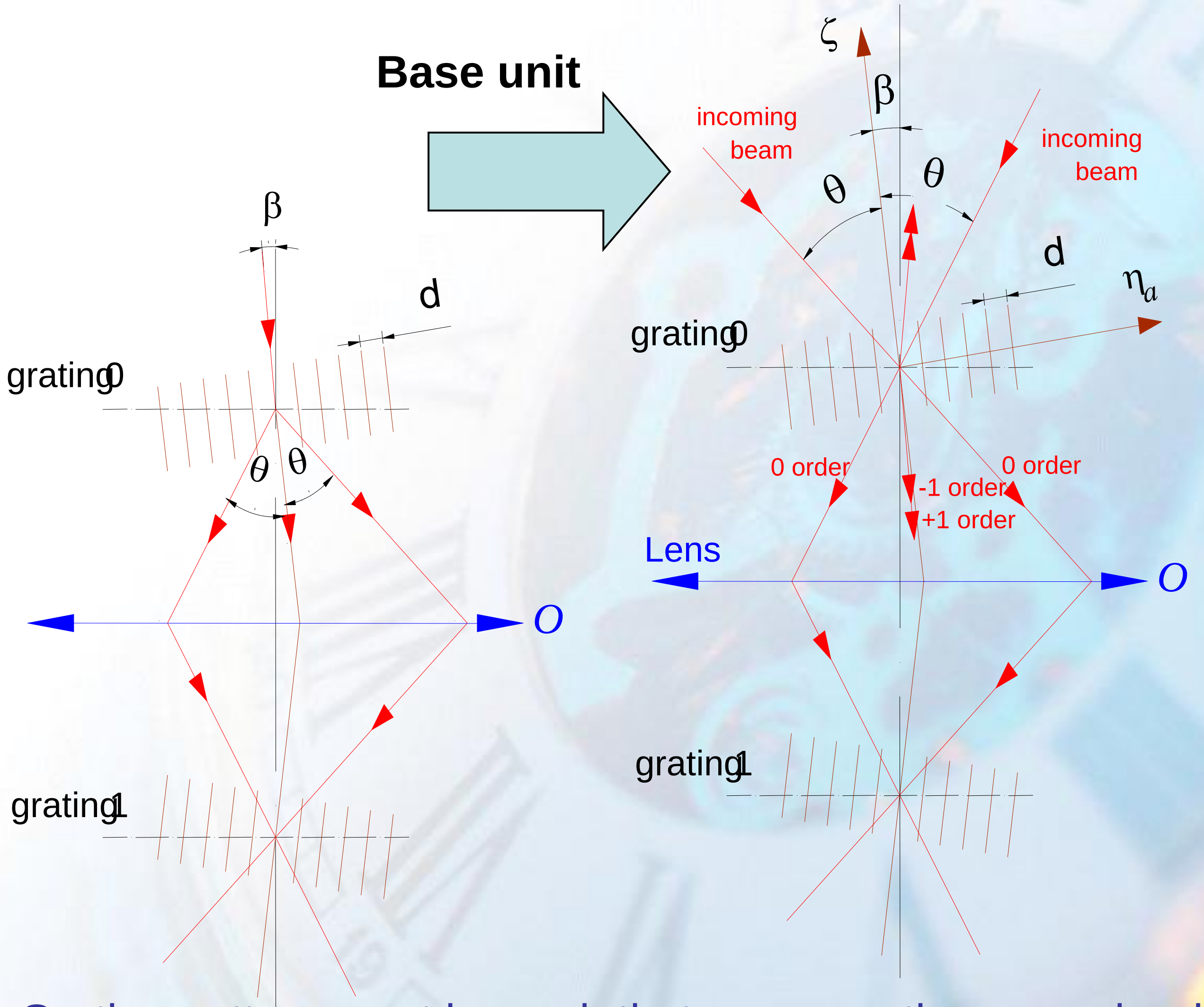




SPF with holder. EUV Transmission spectrum

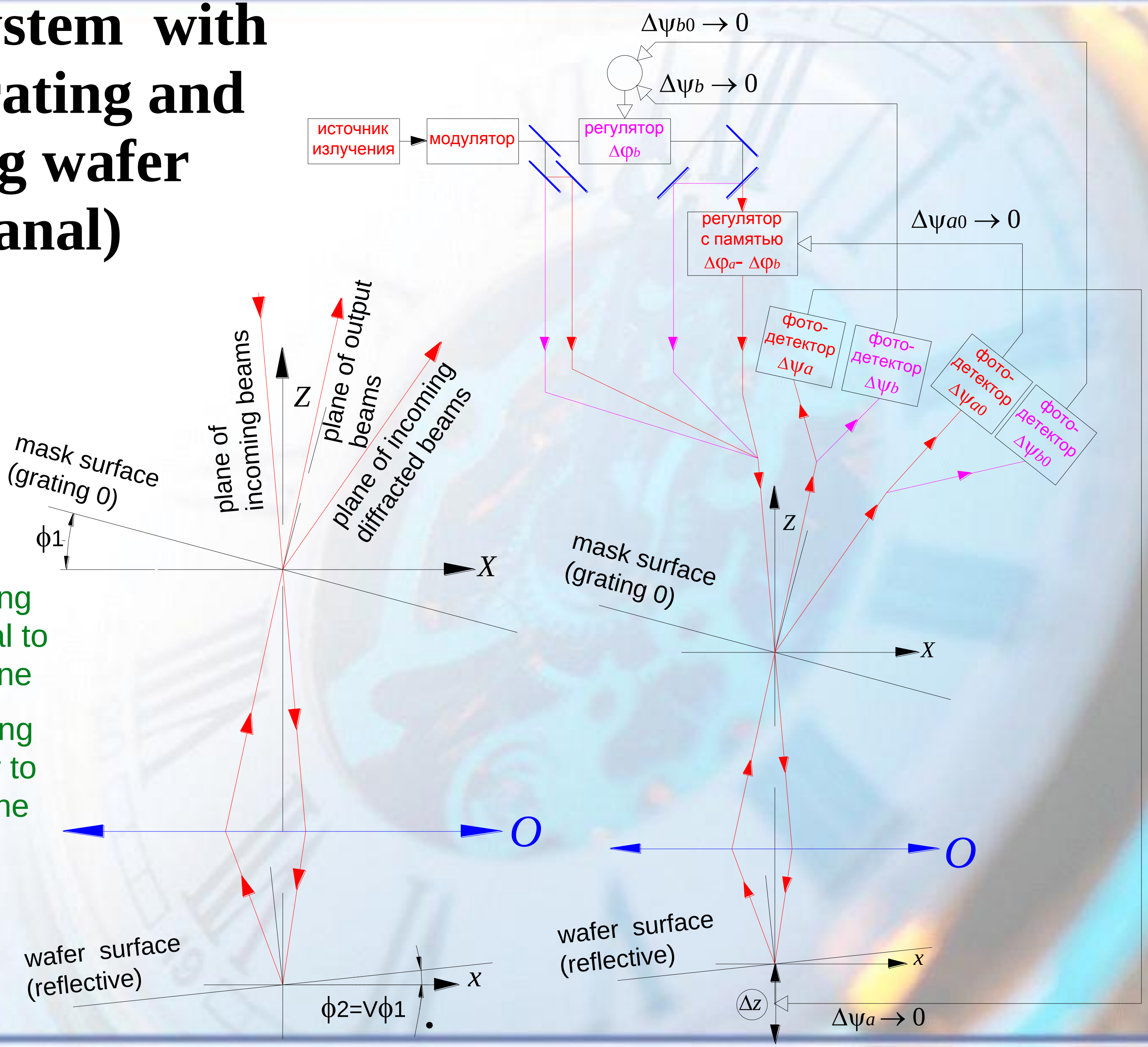
Possible area about 1-4 cm2 for MLS grown on LOR

Precise mechanical and optical systems development providing for nanometric scale precision for adjustment and focusing of nanolithographer optical system.



Grating pattern must be such that suppress the second order of diffraction.

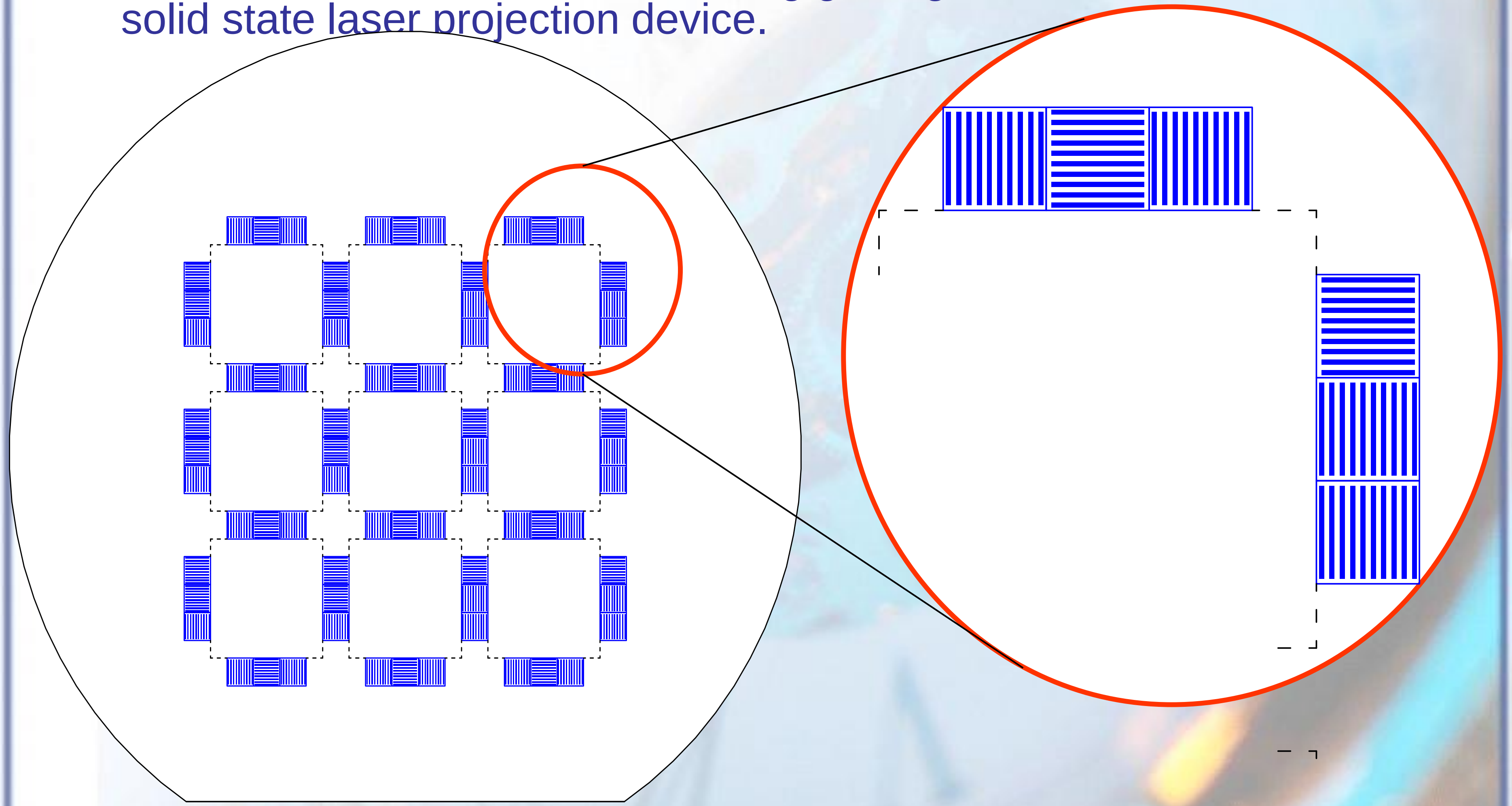
Focus system with single grating and reflecting wafer (single canal)



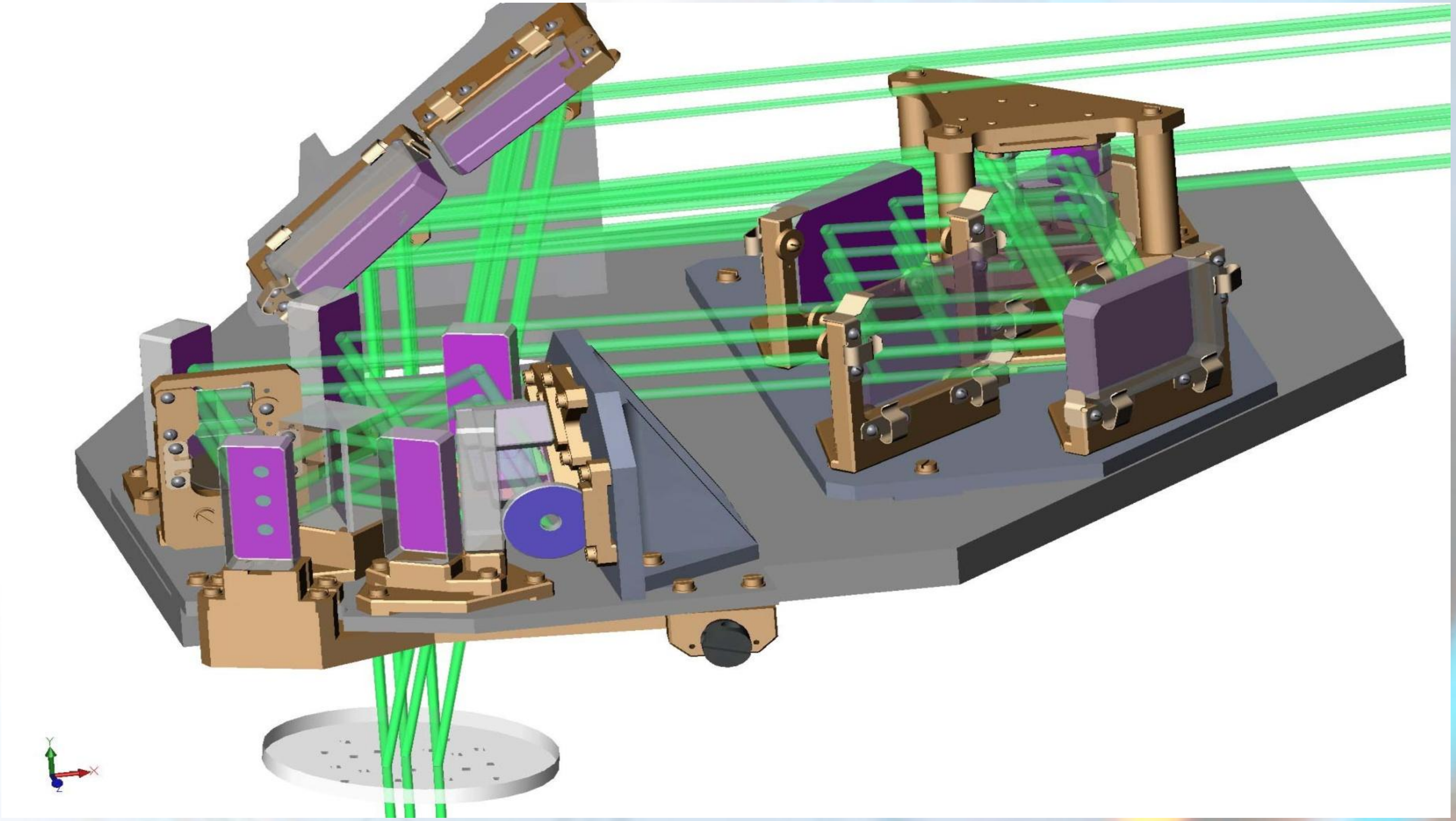
Plane of incoming beams is normal to the drawing plane

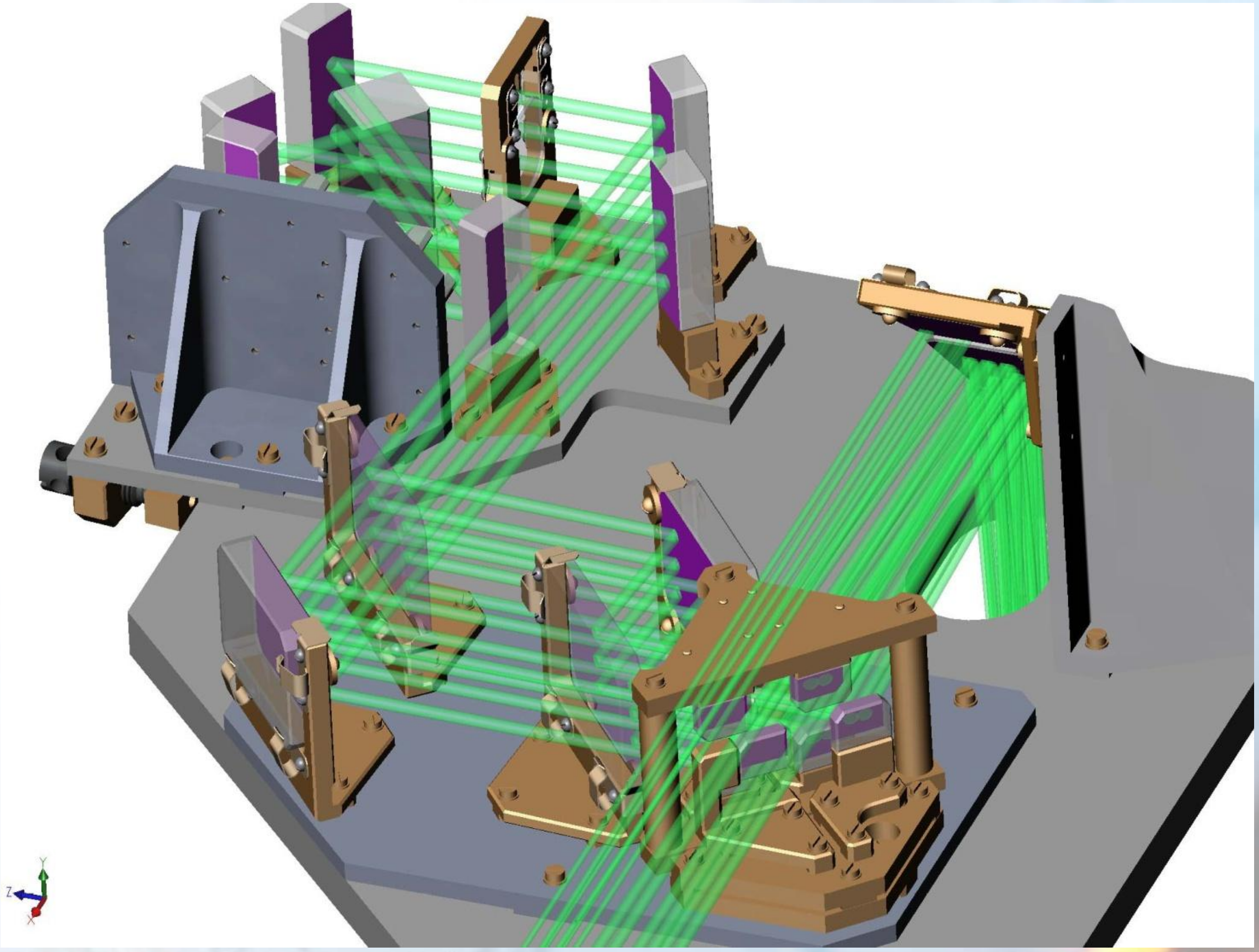
Axis of the grating is perpendicular to the drawing plane

- An original **technology for photomask production** is developed in the Ioffe Institute for the EN. It includes originally invented mask pattern and construction, and technologies for deposition both reflecting and absorbing structures on the mask surface. The f**ocusing and alignment systems represent by itself multichannel** interferometers using gratings and second harmonics solid state laser projection device.

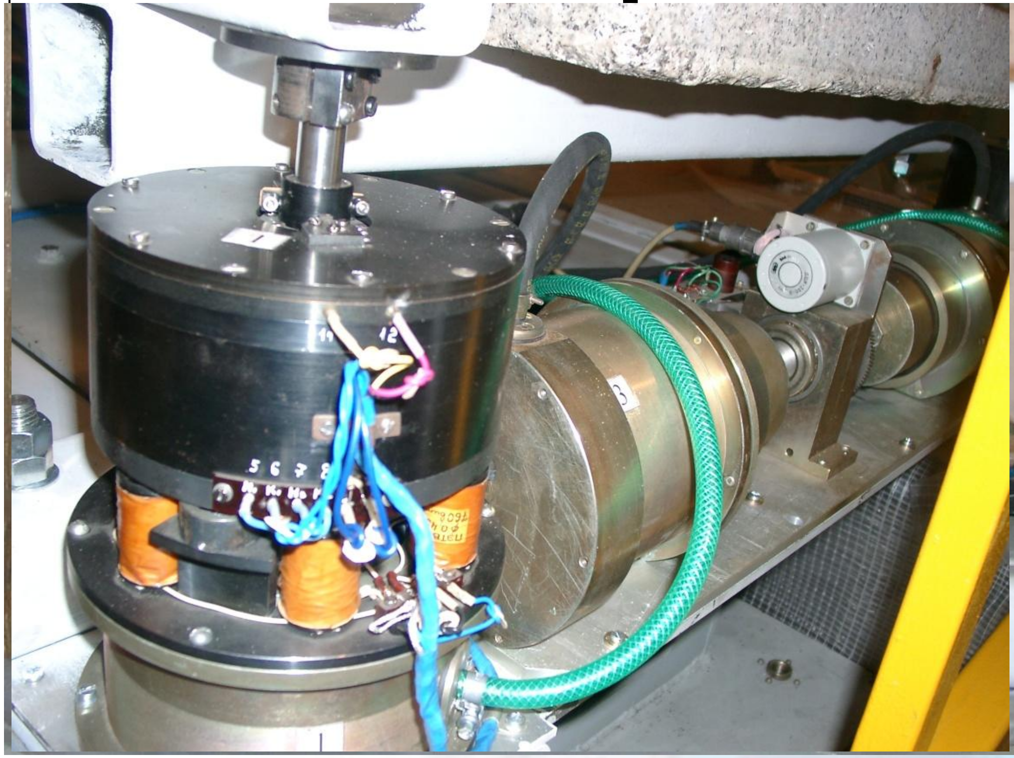


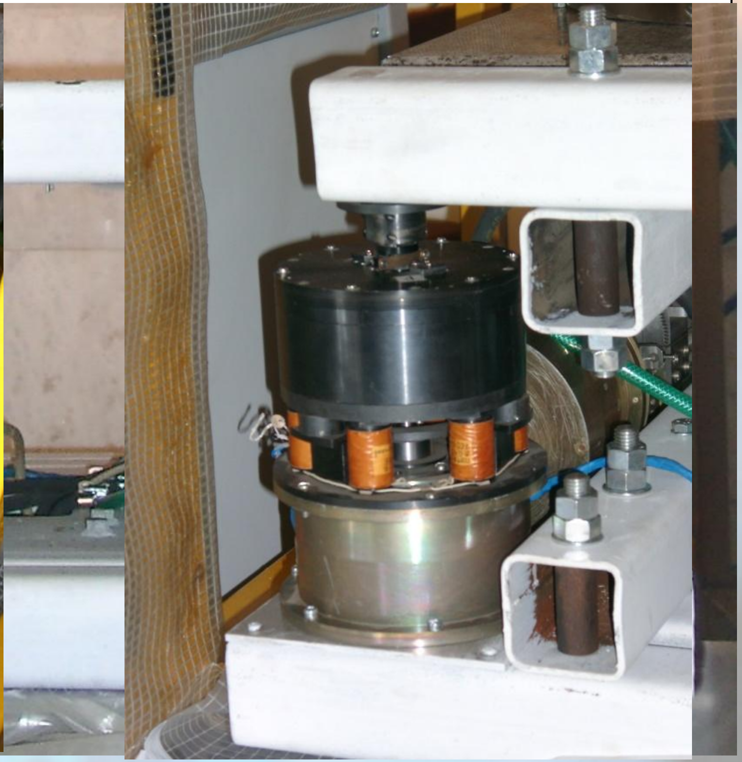
Scheme of the focusing system realization





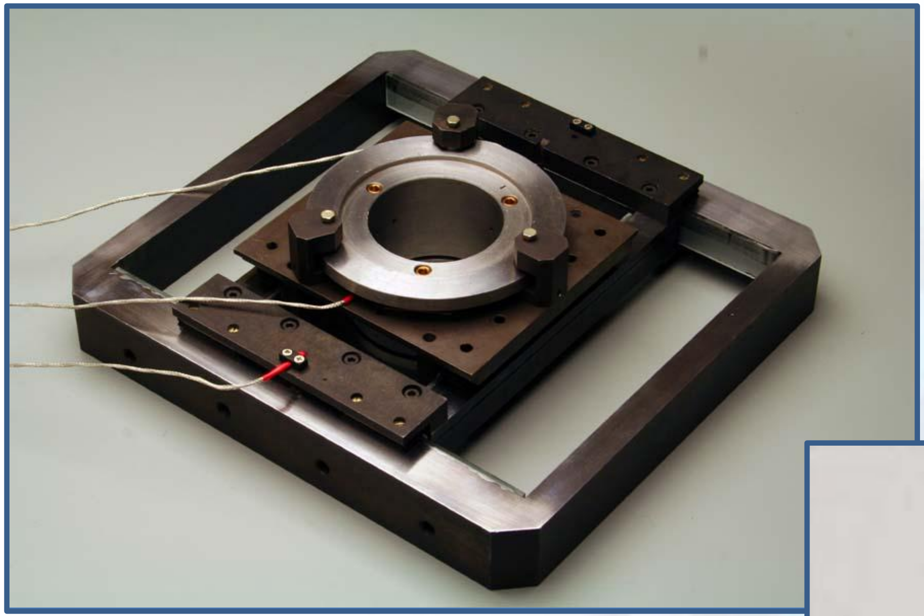
Vibroprotective table

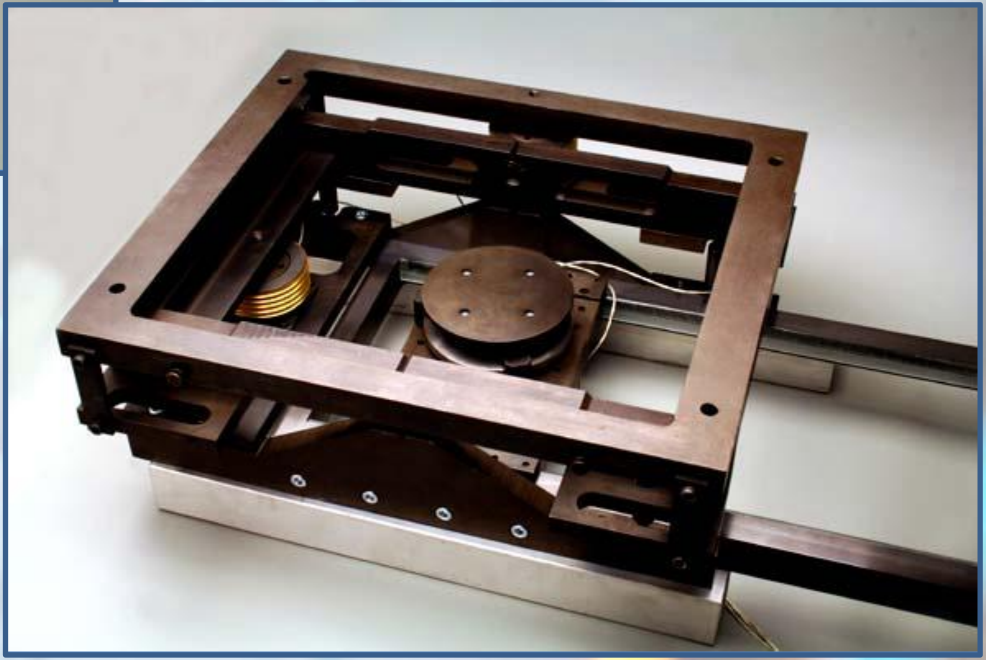




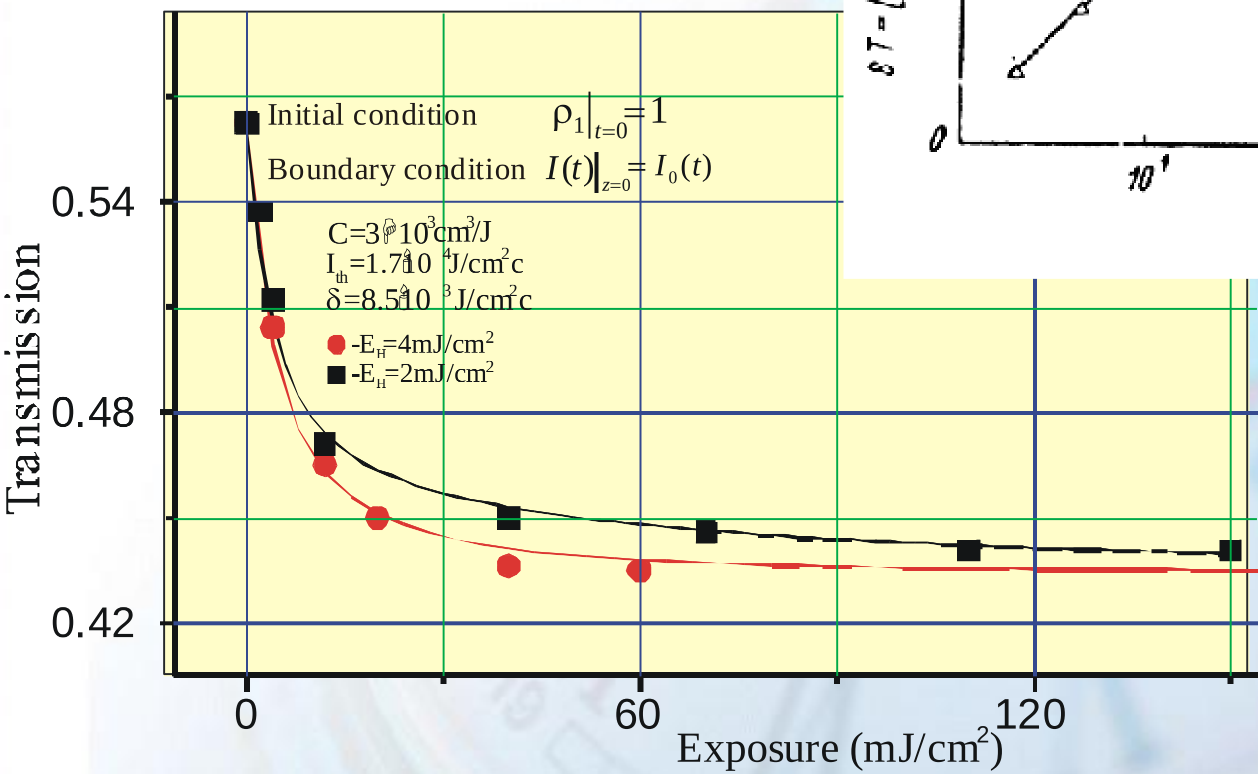
- The EN modules are installed on massive granite plate of **vibroprotective table**. The table has been invented in the Baltic University (St. Petersburg) and later finished off in conformity with the EN needs. The table has high performance characteristics and provides both passive and active vibroprotection including infralow frequencies.

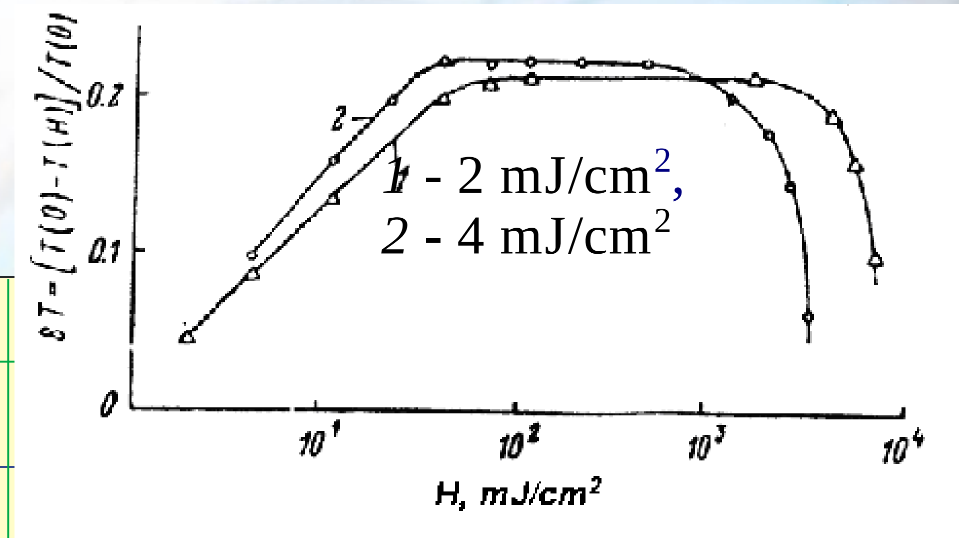
Piezopositioners





Phenomenological model of the non-linear photoresist





Estimated parameters of inorganic nonlinear photoresists

Sensitivity: $C = 3\ \ 10^{-3}$ cm^3/J,
threshold intensity: $I_{th} = 1.7\ \ 10^4$ W/cm^2,
threshold diffusion width: $\delta = 8.5\ \ 10^3$ W/cm^2.
Dose of $H = h/C = 1.7$ mJ/cm^2 is sufficient for exposure of a photoresist specimen h=50-nm thick.
Pulse threshold dose (at 20 ns) is $H_{th} = \tau I_{th} = 0.34$ mJ/cm^2.
Thus, the necessary dose is accumulated with 5 pulses at the threshold intensity and 20 ns pulse duration.

Computer simulation of the enhancement of the contrast by means of inorganic non-linear photoresist

The best quality of image is reached under conditions:

$$\ln\left(\frac{1/\rho_{1s}+\gamma}{1+\gamma}\right)=\alpha_2 C I_p F(I_p) T_p$$

$$\exp\left(2\frac{I_p-I_{th}}{\delta}\right)\left(1-\frac{2I_p}{\delta}\right)+1=0$$

where $\gamma = (\alpha - \alpha)/\alpha$

I_p, T_p - intensity and time of pulse

I_{th} - threshold intensity

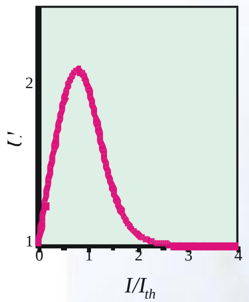
δ - smearing of threshold intensity

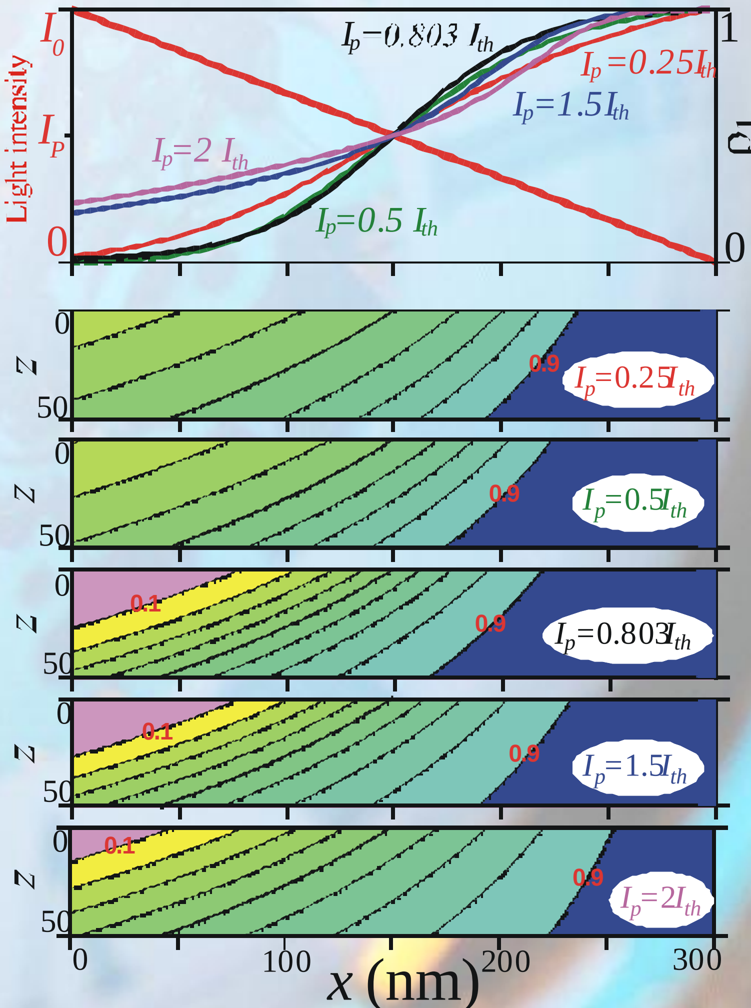
The contrast enhancement

$U=(\delta r_1/\delta x)/b$

(at $r=r_{1s}$, $b=1/I_p(\delta I/\delta x)$)

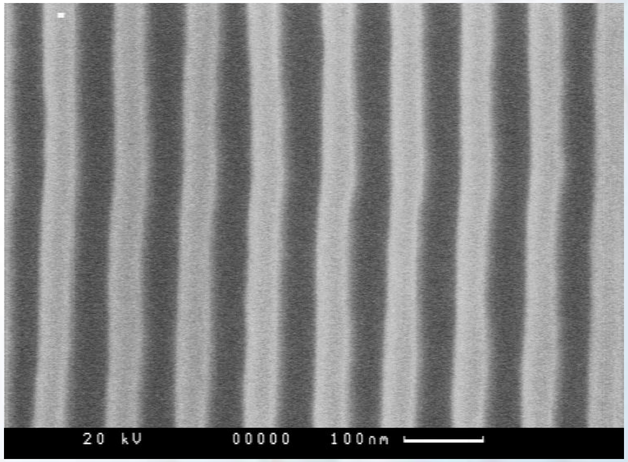
dependence on illumination intensity

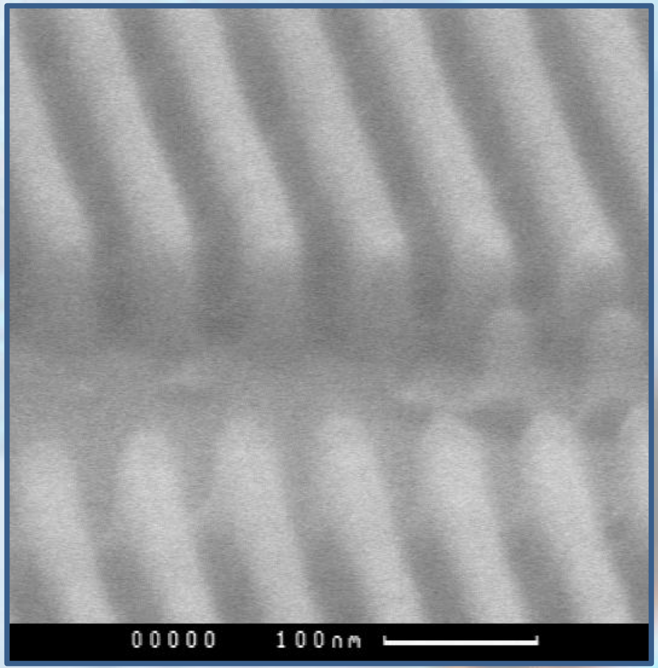




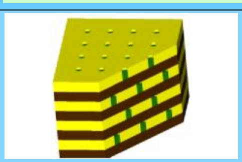
Experiments on the **EUV exposure** have been carried out with synchrotron 13.4nm emission and, in a tentative form, on the Experimental Stand, the auxiliary setup of the Ioffe Institute, for λ = (13.4 ± 0.3) nm.

- Patent of RF #82349, 03.12.2008.
- The results obtained suggest that the **EUV sensitivity** should be some lower than that at λ = 193 nm.
- As_2S_3 films exposed on the synchrotron, after the chemical development, demonstrated distinct interferention structure with 30-40 nm stripes and space-stripe period about 50-100 nm thereby confirming **good resolution ability** of the material.

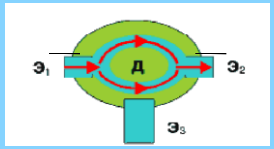


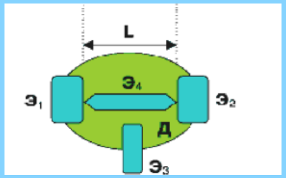


QDC (quantum dot crystal)

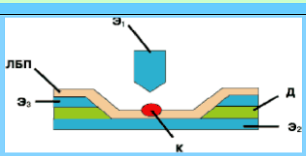


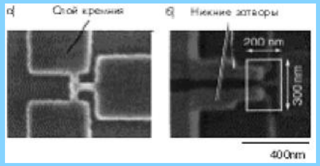
Interference transistor



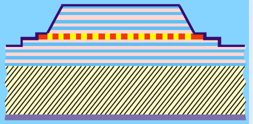


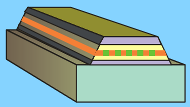
Single-electron transistor



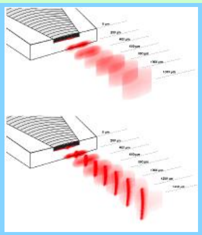


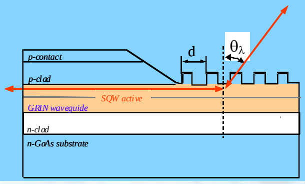
QD semiconductor laser



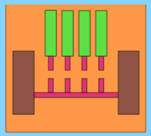


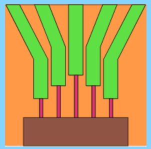
DFB Laser systems





Mesoscopic elements





Photon crystals