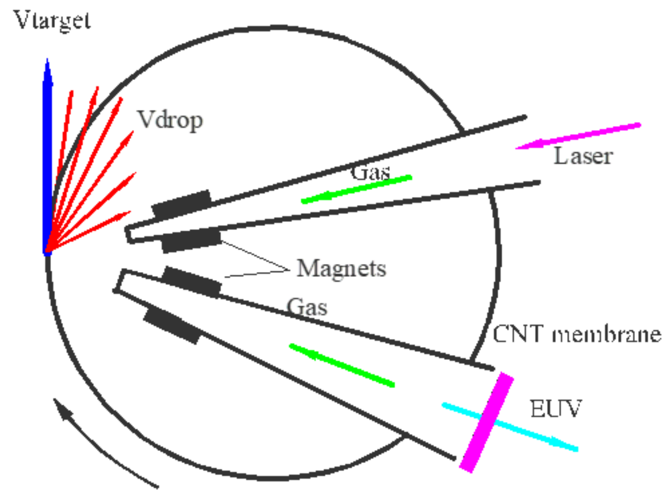
Low debris high-brightness LPP EUV and VUV source with fast rotating target for metrology applications

Konstantin Koshelev, Alexander Vinokhodov, Oleg Yakushev, Yuri Sidelnikov, Vladimir Ivanov, Vladimir Krivtsun, Alexander Lash, Dimitri Abramenko, Mikhail Krivokorytov, Vyacheslav Medvedev, Denis Glushkov, Pavel Seroglazov, Samir Ellwi

Key features of source with fast rotating target

Protected by patents
1.US 2019/0166679 A1
2. US 16/535,404

The principle of protection against drops due to fast rotation of target - redirection of most big droplet debris away from laser and EUV windows



- **Using a combination of debris mitigation technologies, both conventional and innovative: fast rotation of target and CNT membranes.**
- **Undisturbed target surface -** excellent energy and position stability at high PRR
- **No synchronization between the laser pulse and the target** - ease of source setting and reliability of operation
- **Very low fuel consumption -** high uptime
- **Efficient power dissipation from target-** lasers with power of more 1 kW can be used.
- **It is possible to vary the emission spectrum in EUV and VUV ranges** -changing the type of fuel. Fusible metals Sn, In, Li, Pb, Bi and their alloys can be used as fuel.

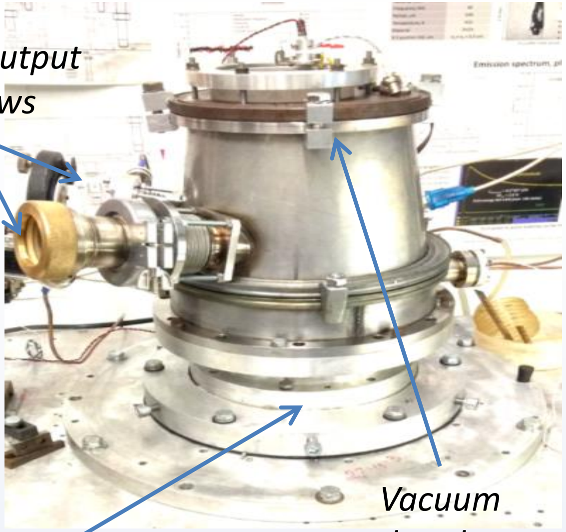
First generation of the source-ACTEST 1

30W fiber laser parameters at power density $5*10^{10}$W/cm^2

In-band source parameters at usage of Sn/In eutectic alloy

Laser mode	PRR, kHz	Duration ns	Energy mJ	CE, %/2π sr	Size, µm	Brightness, W/mm^{2}sr (at plasma)
T4	30	4	0.89	0.9	26	80
T3	60	2	0.44	0.75	22	100
T2	100	1	0.27	0.4	22	55
T1	600	0.18	0.04	0.09	20	20

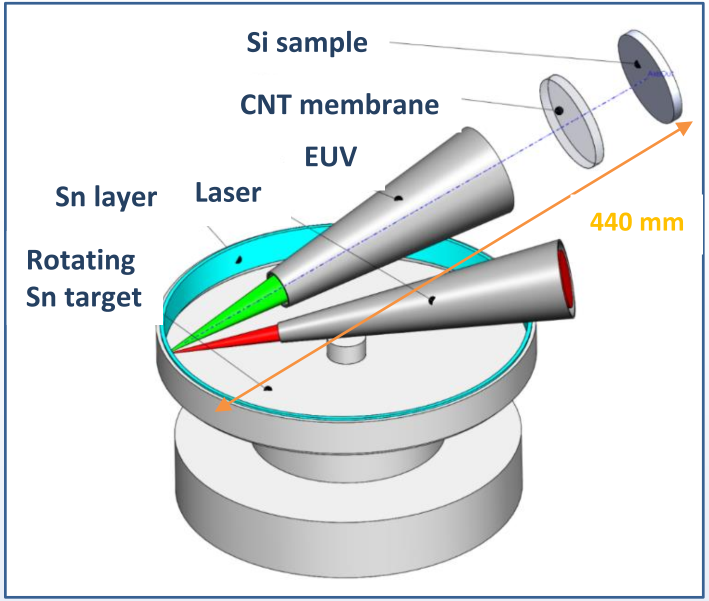
Photo of ACTEST 1



Standard deviation of EUV pulse dose(128 pulses): ~ 0.5%.

Debris mitigation technologies

Debris deposition experiment design



#	Method	Parameters	Type of debris
1	Fast rotation of target	V_{azim} = 120 m/s @ 200 Hz	Large and slow (≤100 m/s) droplets
2	Protection shields	Metal cones $\Delta\Omega_{EUV}$=0.014sr	Randomly scattered all type of debris
3	Magnetic fields	Magnetic induction up to 0.5T	Charged particles (ions, small droplets…)
4	Gas (Ar) counter flow	Gas consumption ~0.1 mbar*L/s	Vapor, ions, small droplets
5	CNT membrane	80% transmission of λ=13.5nm	All type of debris

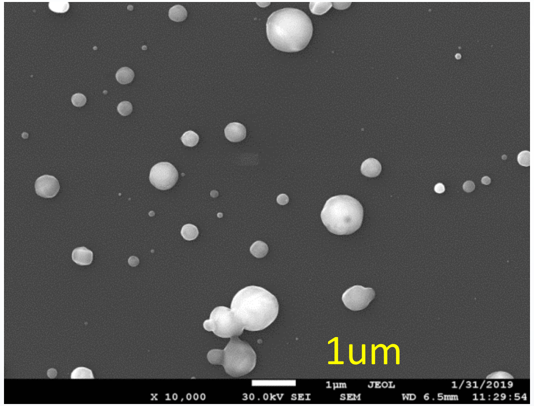
Altogether 200 hours of measurements
More than 40 Gshot

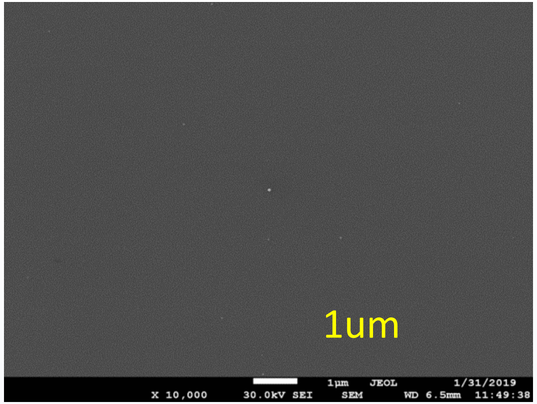
Droplets vs rotation frequency of target

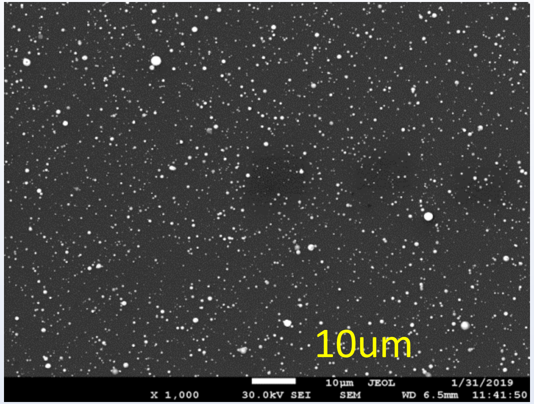
Slow rotation (40 Hz)

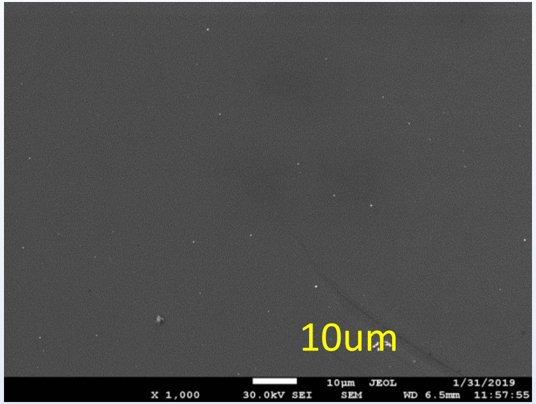
Fast rotation (more 200 Hz)

(without using of CNT membrane)







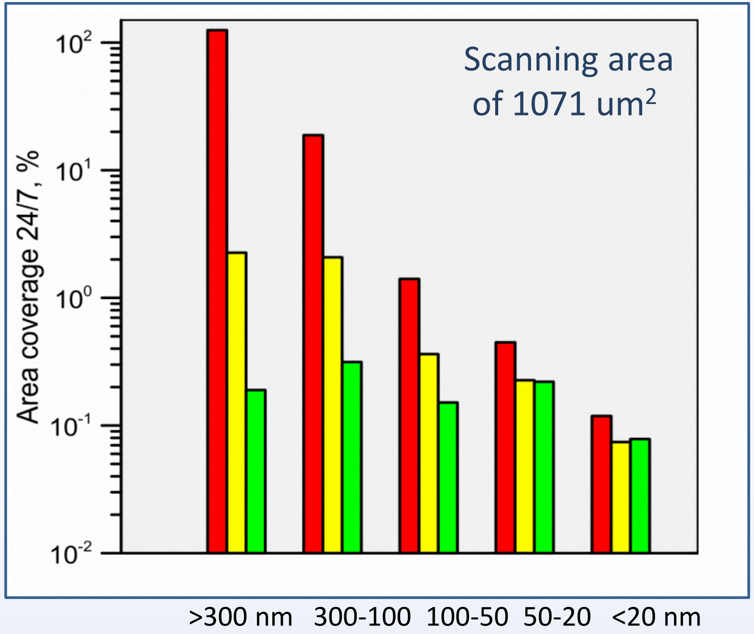


SEM scans of Si sample after 5 hour exposition at 60 kHz (which corresponds 1 Gshot).

The fast rotation frequency eliminated most of the large droplets.

Area coverage of the Si sample by droplets vs droplets size

The distribution of droplets by size recalculated
from 5 hours exposition to 24/7 cycle



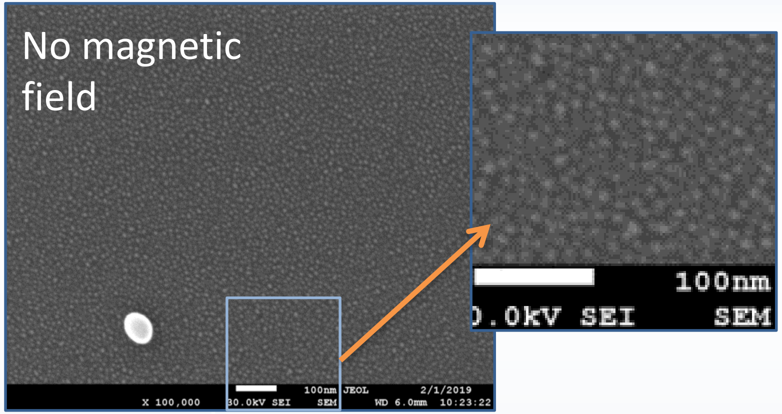
40 Hz (24 m/s); no debris mitigation systems
40 Hz; (24 m/s); debris mitigation systems
200 Hz (120m/s); debris mitigation systems

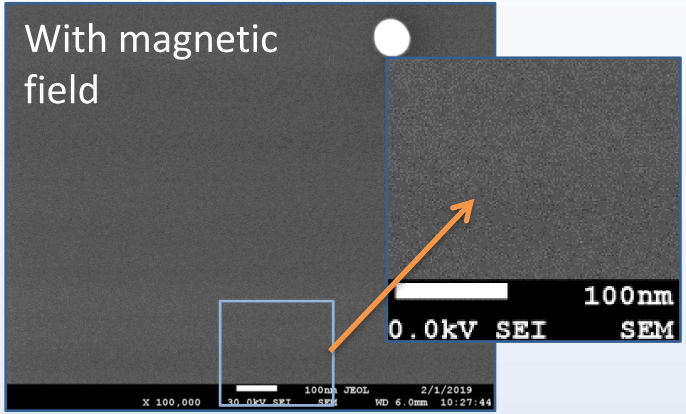
Experiments without usage of CNT membrane

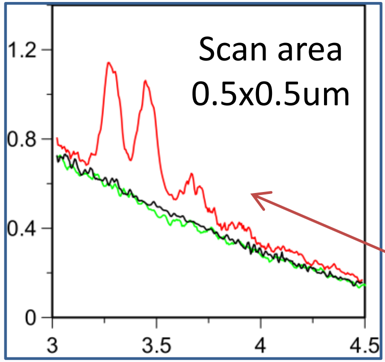
- At **40 Hz without debris mitigation systems** the main role play droplets with d>300 nm. During 24/7 cycle (36 Gshot) these droplets would cover more than 100% of the Si sample surface.
- **At 40 Hz with debris mitigation systems** a coverage of droplets with d>300 nm decreases down to 2% of full surface and total coverage by droplets expected to be around 4% during 24/7 cycle.
- **At 200 Hz** high rotation frequency in 1000 times reduces droplets with d>300 nm. The total drop coverage could be estimated as 0.7% during 24/7 cycle.

Protection by magnetic field

SEM scans of Si sample after 1 Gshot

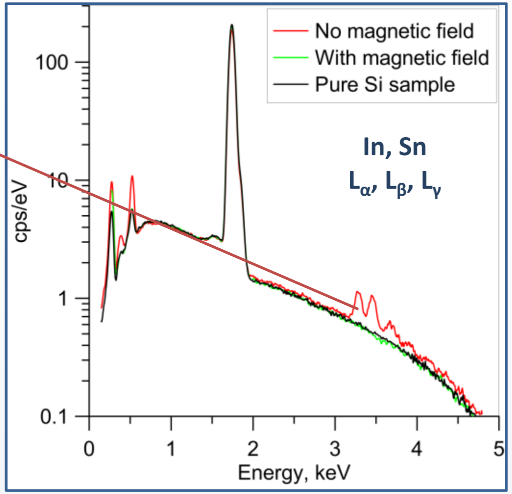






Deposition level lower than measurements sensitivity

X-ray spectrum after 5 Gshot



Average deposition rate without magnetic field can be estimated as < 1 nm/1 Gshot and with magnetic field < 0.01 nm/1 Gshot.

That corresponds to a reduction transmission of in-band radiation at rate less 2% per 24/7 cycle.

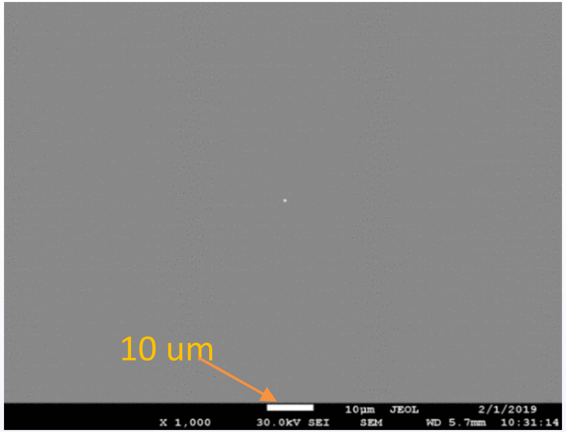
Protection by CNT membrane

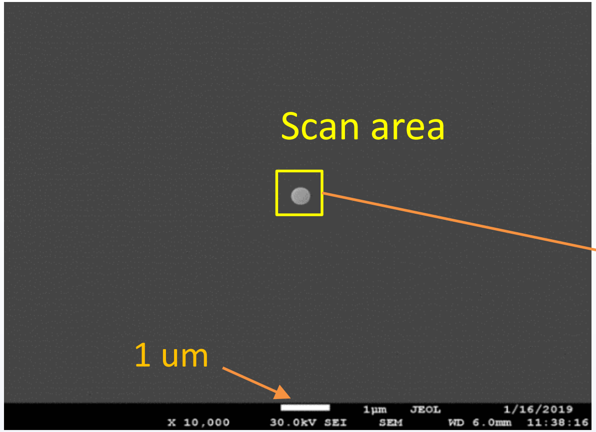
CNT membrane is thin film from chaotically intertwined carbon nanotubes.

Parameters of CNT membrane: d~70-90nm, 80% transparency of in-band radiation.

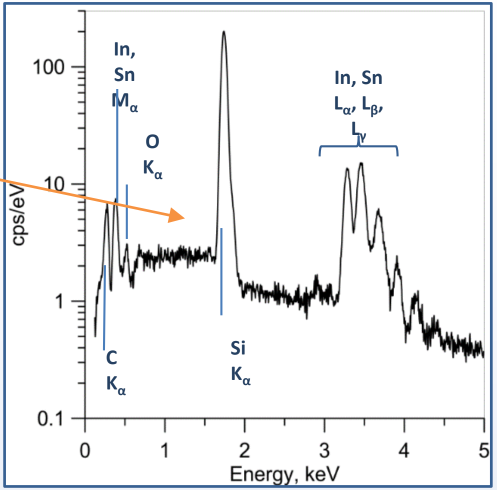
The membrane is a replaceable component.

SEM scans of the Si sample located behind CNT membrane after 1 Gshots





X-ray spectrum



Particles consist of Sn and In

On the square of ~0.16 mm^2 was found only 2 droplets in size ~400 nm, what corresponds estimated time of 5% degradation of Si sample surface of about 10^5 hours. Small droplets and ion deposition were not detected.

Scalability of the source: from ACTEST 1 to ACTEST 2

Photos of ACTEST 2

ACTEST 1 is a laboratory tool

ACTEST 2 is a prototype of commercial tool

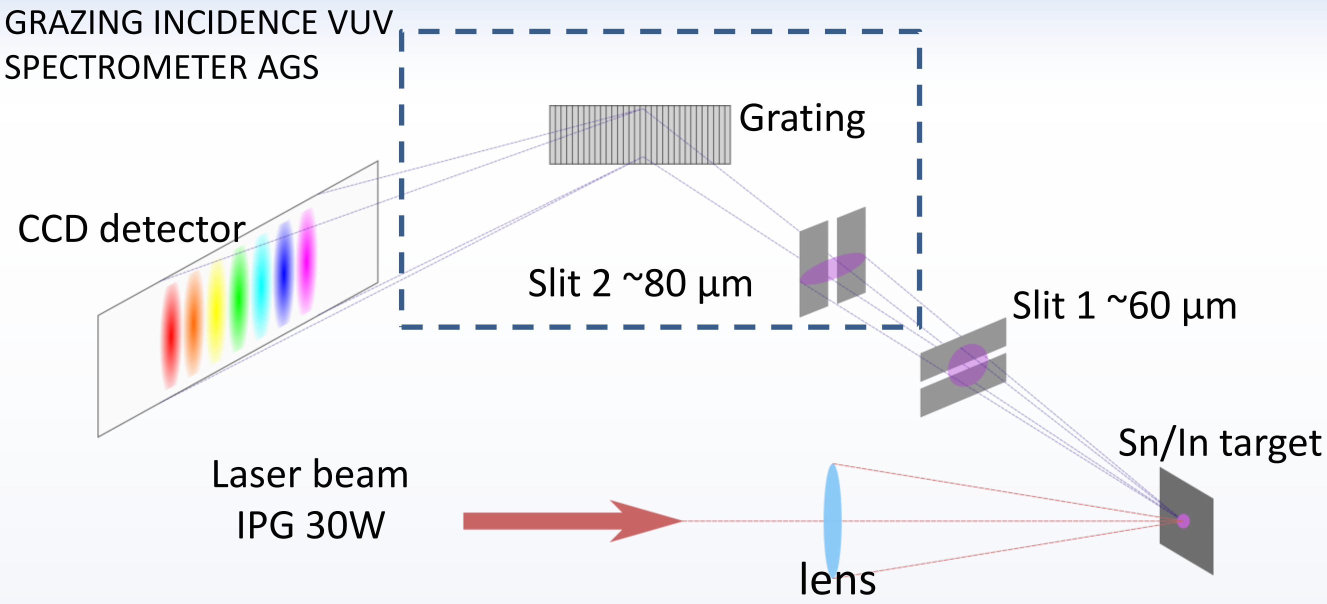
What's new in ACTEST 2 compared to ACTEST 1 :

- New type of target drive based on magnetic coupling
- Rotation frequency up to 400 Hz (240 m/s)
- Usage of thermal stabilization system of target (power laser more 1 kW)
- Usage of much more solid angle of the EUV collector system (0.12 sr)
- Full automation of the source

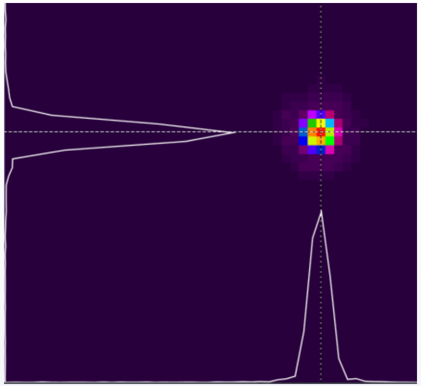
Expected ACTEST 2 parameters based on experiments and RZLINE code modelling at usage 400 W Edgewave laser (InnoSlab, IS serias), 3.2 mJ, 125 kHz, 1.5 ns:

- CE 2%
- Brightness @70 um $\geq$ 300 W/mm^{2}sr (at plasma)
- Collected EUV power (at mirror) $\geq$100 mW

Experiment design in VUV band (60-120 nm)

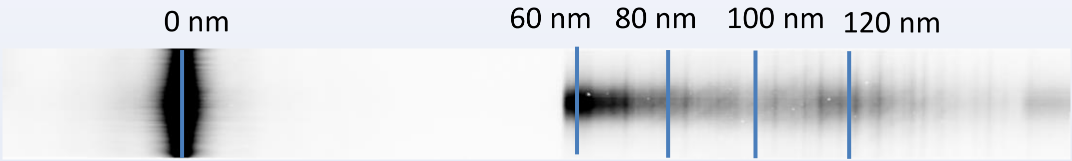


Laser focal spot



20 µm 1/e²

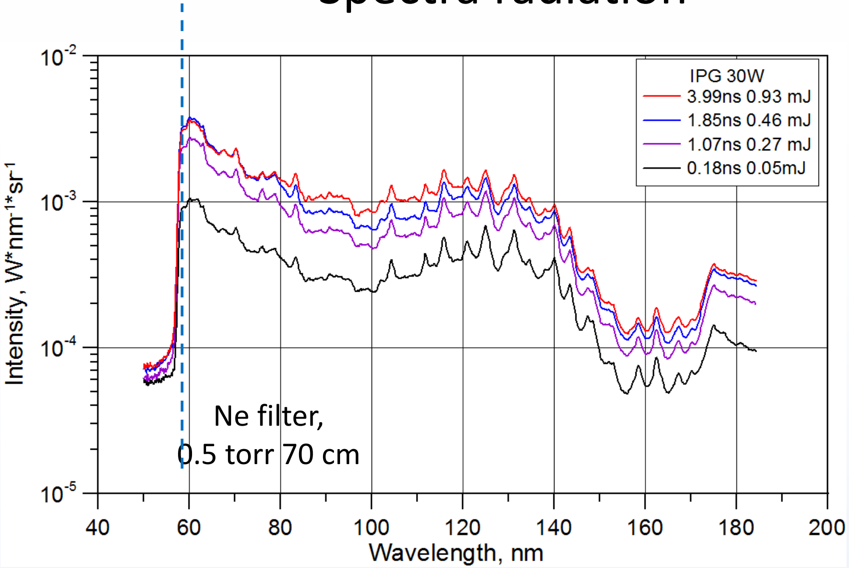
Spectrogram of radiation



Size of source ≤ 50 µm

Source parameters in band of 60-120 nm at usage of 30 W laser

Spectra radiation



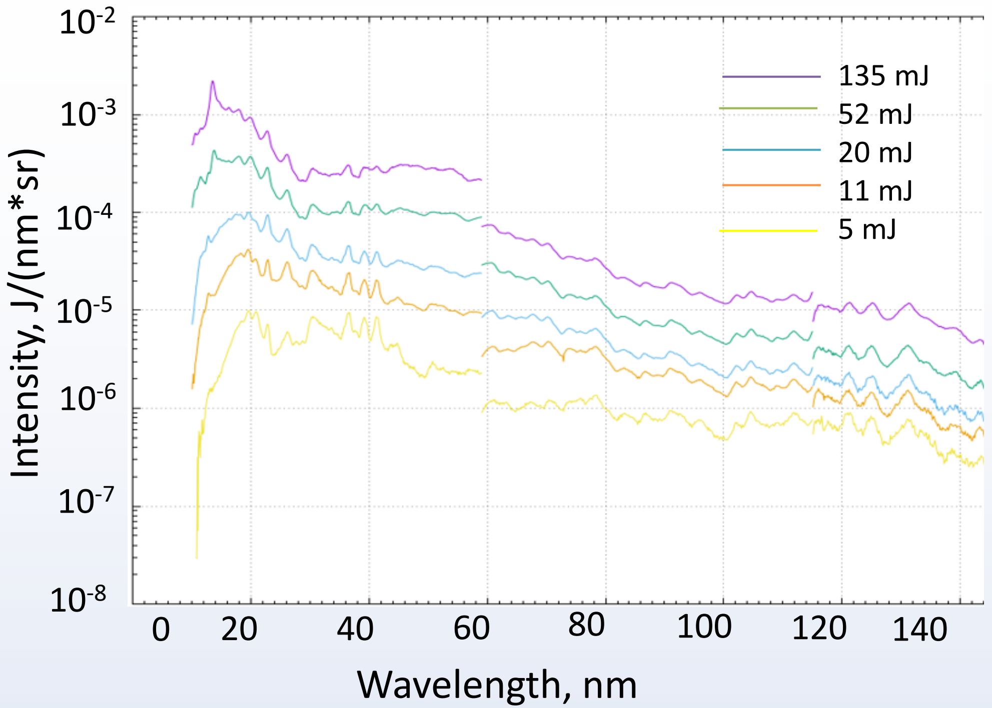
Energy parameters in full bands of 60-80 nm and of 80-120 nm (ACTEST-1, IPG laser, T4 mode - 1mJ, 4ns, 30kHz, d=20 um):

Parameter	60-80 nm	80-120 nm	60-120 nm
Intensity, mW/sr	$4.5*10^{-2}$	$4.2*10^{-2}$	90
Brightness, W/(mm²*sr)	23	21	44
CE ,%/sr	0.16	0.15	0.31
Collected power, mW/0.014sr	48	45	1.3

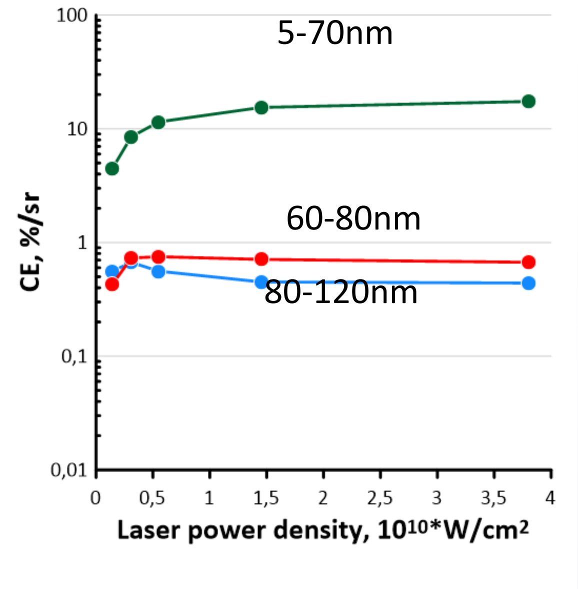
Small CE is connected with the small focal spot size of 20 µm, when the plasma life time is not enough for achieve optimal parameters.

Source parameters in bands of 60-120 nm and 5-70 nm at usage Nd-YAG laser with high pulse energy ($\Delta\tau$=14 ns, d=180 nm)

Spectra radiation



CE in band of 60-80 nm, 80-120 nm and 5-70 nm vs power density



Scalability of the source in bands of 60 -120 nm and 5 -70 nm

Expected ACTEST 2 parameters in bands of 60-80 nm, 80-120 nm and 5-70 nm at usage 400W Edgewave laser, 3.2 mJ, 125 kHz, 1.5 ns, d=180 nm ($P \cong 10^{10} W/cm^2$)

Parameter	60-80 nm	80-120 nm	60-120 nm	5-70 nm
Intensity, W/sr	>2.15	>2	>4.15	>52
Brightness, $W/(mm^2*sr)$	>80	>85	> 165	>2100
CE ,%/sr	>0.5	>0.75	>1.25	>13
Collected power, W/0.12 sr	>0.24	>0.26	>0.5	>6

Conclusions:

1. **We report the realization of low debris LPP EUV and VUV source for actinic inspection. The source is based on usage of two new debris mitigation technologies: fast rotating liquid metal target and CNT membrane.**
2. **The EUV brightness at plasma of about 100 W/mm^2 sr has been demonstrated for 60 kHz low power (30 W) IPG fiber laser.**
3. **5 % degradation of the CNT membrane lifetime connected with droplet debris is about 7 weeks. 5 % degradation of the CNT membrane lifetime connected with ion deposition is longer than 2.5 weeks.**
4. **The assembly of the new generation of the source for use of 400 W laser is currently being completed. The expected brightness at 13.5 nm is more than 300 W/mm^2 sr at using of 400 W laser.**
5. **When using tin-containing fuel, the source is capable of producing high-brightness radiation in the 60-120 nm range (≥ 44 W/(mm^2*sr).**

Thank you for attention

Address: 108840, Moscow, Troitsk, Russia,
Promyshlennaya 2B,
Tel.: +74956656501; +79166861316
E-mail: info@rnd-isan.ru

Address:
108841, Moscow, Troitsk, Russia, Promyshlennaya, 2B,
Tel.: +7 (926) 146-87-86
E-mail: enquiry@euvlabs.net

Address: Eindhoven, The Netherlands, High Tech Campus 9, 5656 AE
Tel.: +31(0)40-230-42-42
E-mail: info@isteq.nl