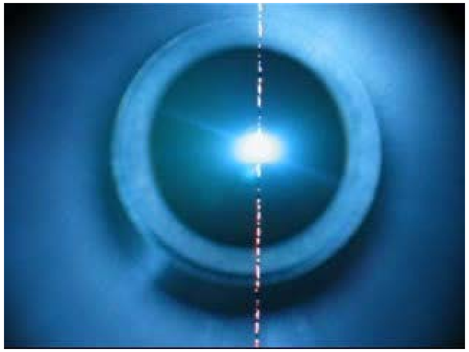
Gas discharge and laser produced plasma sources at XTREME technologies



An update

Uwe Stamm

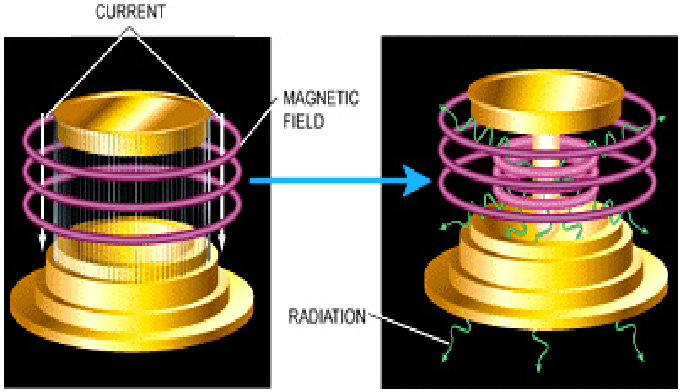
XTREME technologies, Göttingen and Jena, Germany

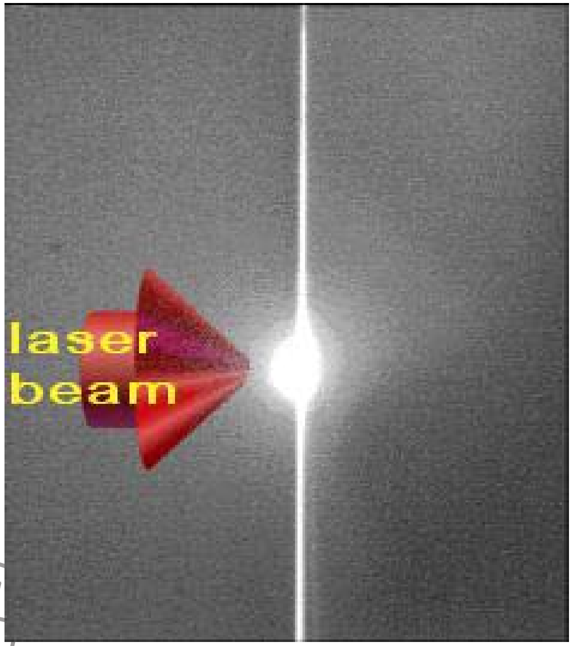
International SEMATECH EUV Source Workshop,
23 February 2003, Santa Clara, CA, USA

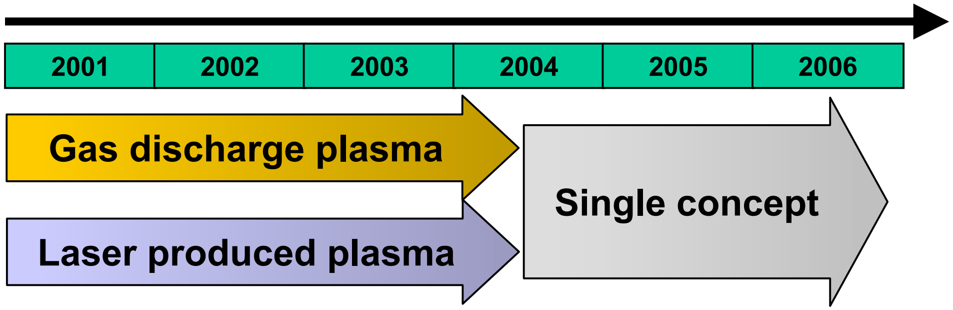
XTREME technologies

Taking light to new dimensions…

XTREME technologies – EUV Source development







2001	2002	2003	2004	2005	2006

Gas discharge plasma

Laser produced plasma

Single concept

XTREME technologies GmbH:
EUV joint venture between
Lambda Physik AG and Jenoptik LOS GmbH

Mission:
Development, manufacturing and marketing of EUV sources for lithography and advanced applications in micro- and nano-technologies

MEDEA+ EUV Source Development – 2001 - 2004

Participants:

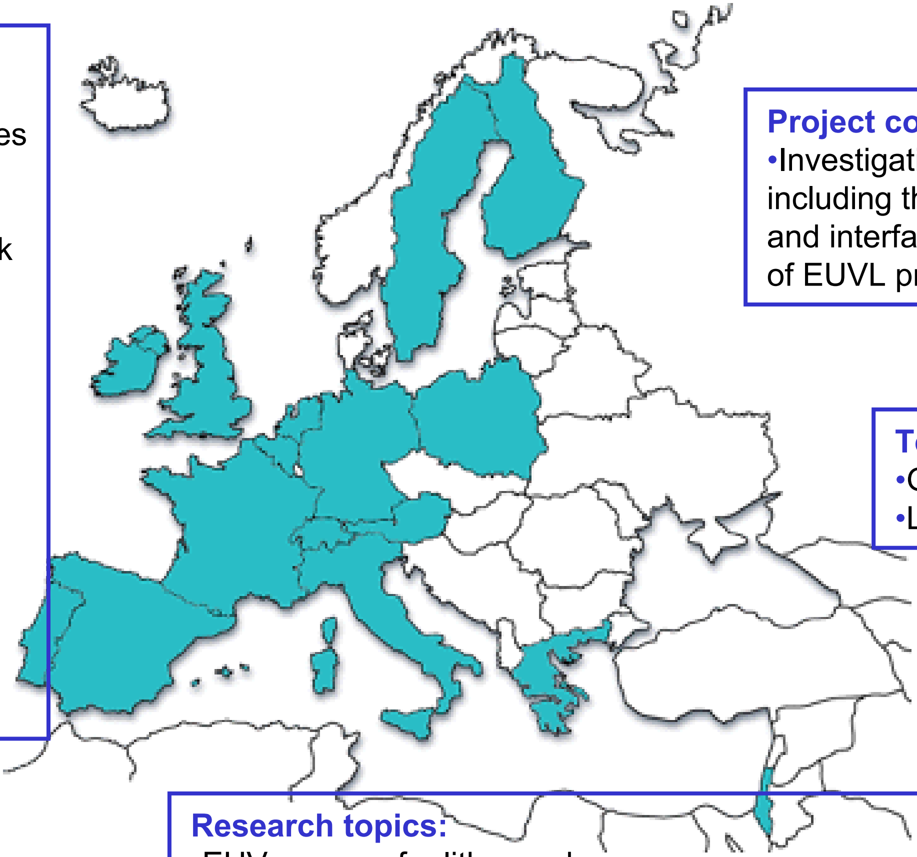
Germany
- XTREME technologies (coordinator)
- Philips Extreme UV
- Jenoptik Mikrotechnik
- AIXUV
- Zeiss

France
- Alcatel
- CEA
- Thales

Netherlands
- FOM

Sweden
- Innolite

Poland
- IOE



Project content:
- Investigation on solutions for EUV sources including their characterization and interfacing to first generation of EUVL production tools

Technology:
- Gas discharge produced plasma
- Laser produced plasma

Research topics:
- EUV sources for lithography
- EUV sources for metrology purposes (mask inspection, optics characterization, process development)
- Metrology for EUV source characterization

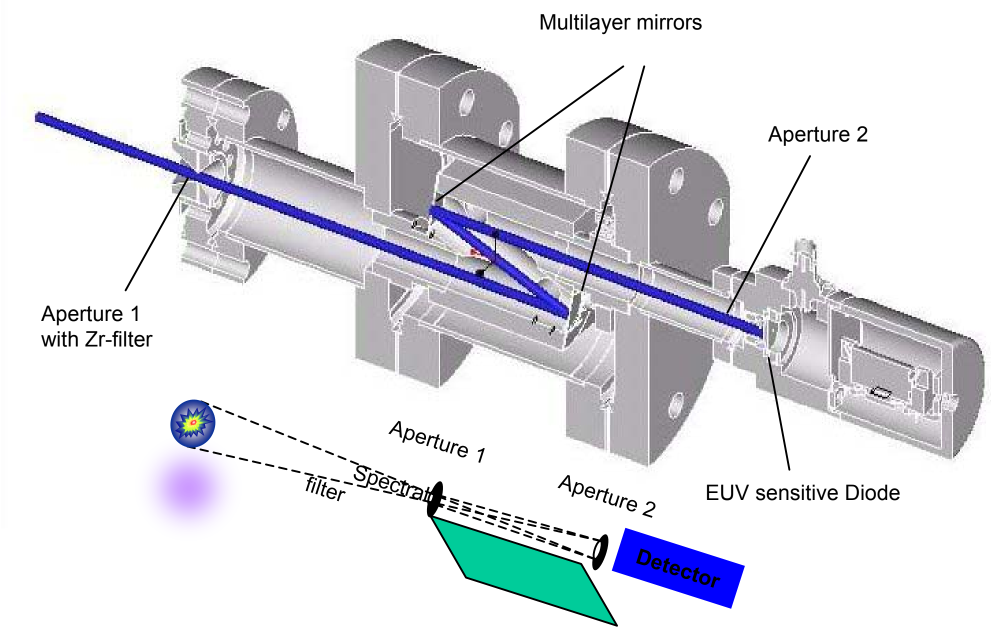
Taking light to new dimensions…

Calibrated Metrology in Use

JENOPTIK
JENA
Mikrotechnik

FOM

AIXUV EUV-Technology



Concept

- EUV band selection by multilayer mirror
- Background cut-off by matched filter
- Junction diode EUV detection

Calibration

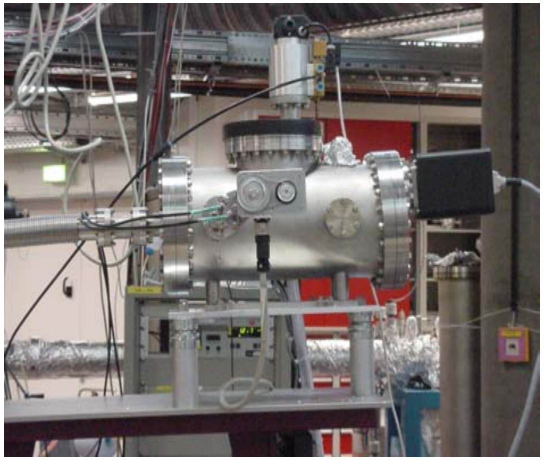
- At-λ calibration of components (PTB @ Bessy II)

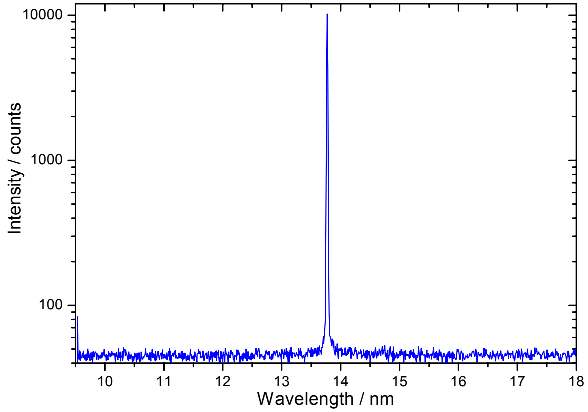
Accuracy

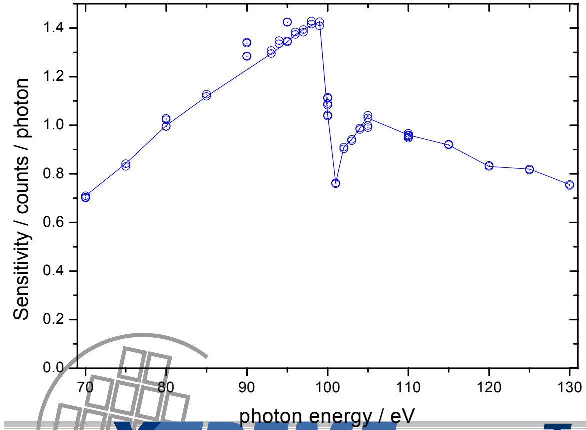
Total error working conditions *< 5 %*

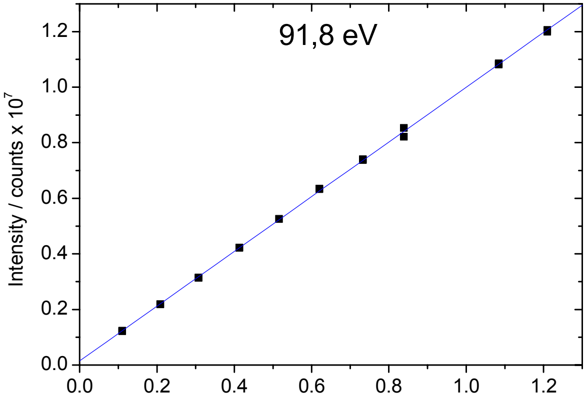
Calibrated Metrology in Use

Calibration of the E-Spec at PTB









Very low stray light background

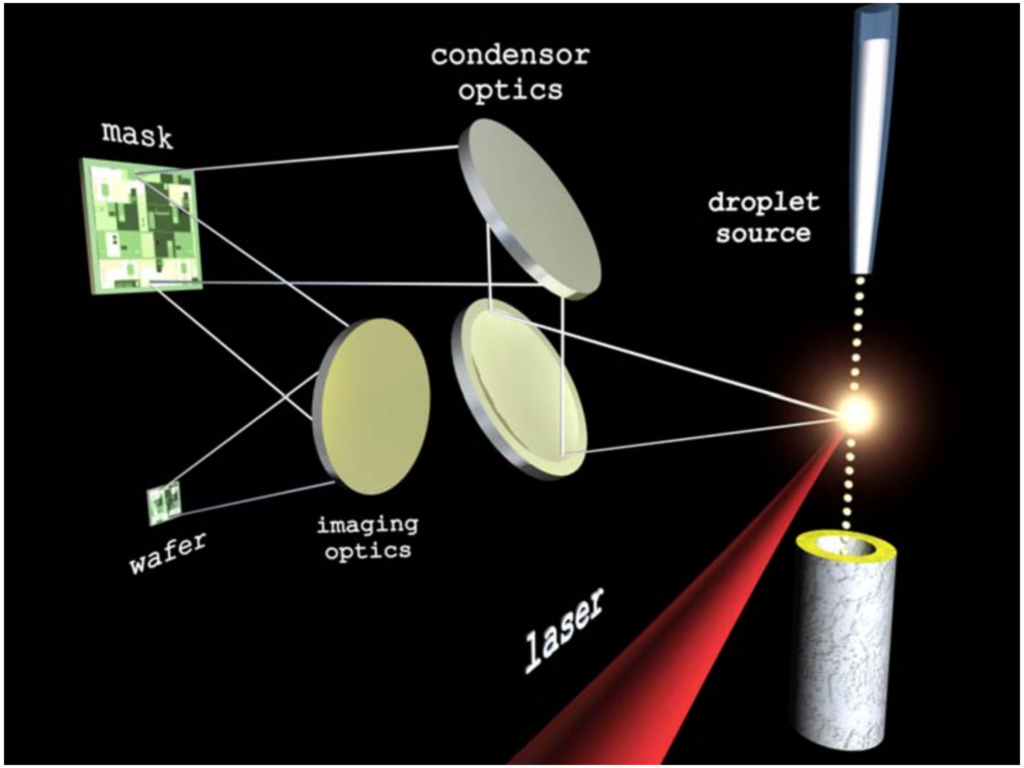
High resolving power
$\lambda / \Delta\lambda \approx 600$

High wavelength accuracy
$\lambda / \Delta\lambda > 800$
(Standard: PTB)

High sensitivity
0.7 - 1.4 counts / photon

Strictly linear

Laser produced plasma EUV source

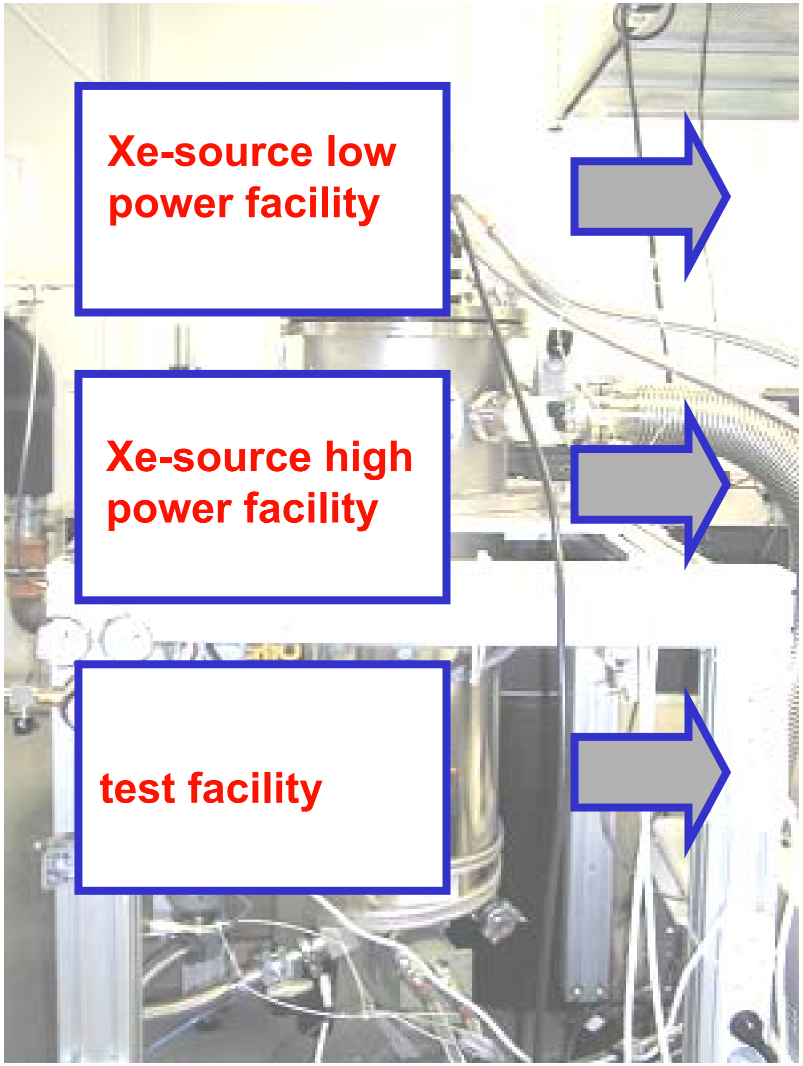


Operating principle

- continuous supply (filament, droplet, etc.) of a mass limited target in the focus of a laser beam
- plasma generation takes place at several cm distance from other hardware
- benign target material (Xe) to minimize optics contamination

Taking light to new dimensions…

LPP operating facilities and tasks



Xe-source low power facility

- fundamental investigations
- components evaluation
- interaction optimization

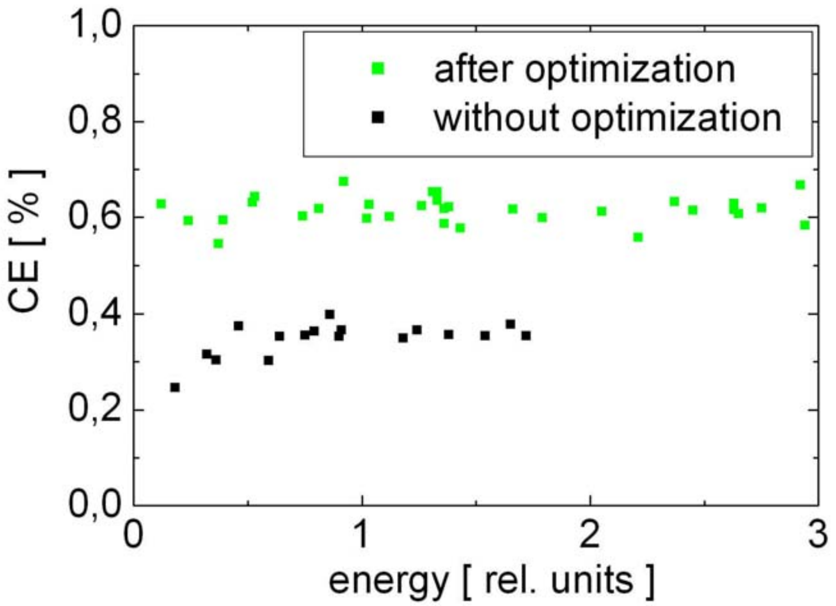
Xe-source high power facility

- high power investigations
- EUV-optics investigations
- stability optimization

test facility

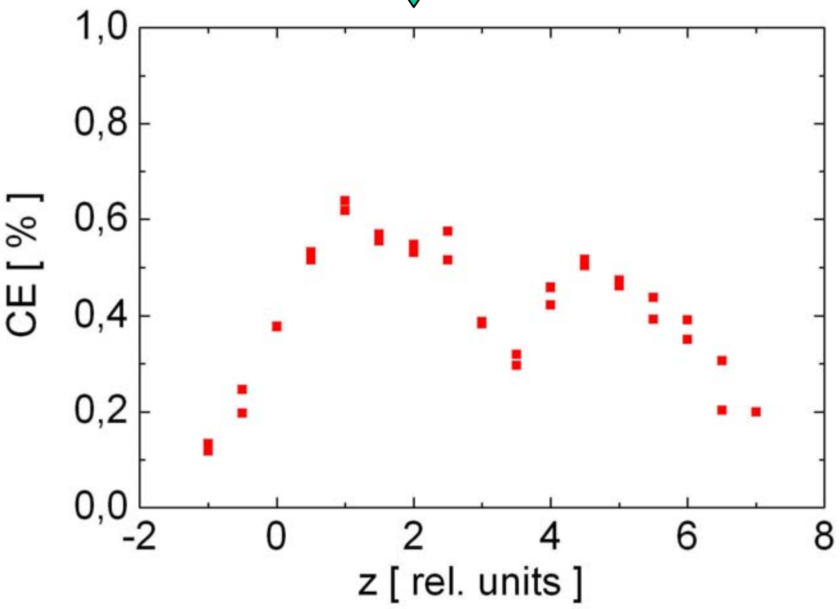
- debris investigations
- plasma physics studies
- alternative emitters

efficiency optimization, Xe-target



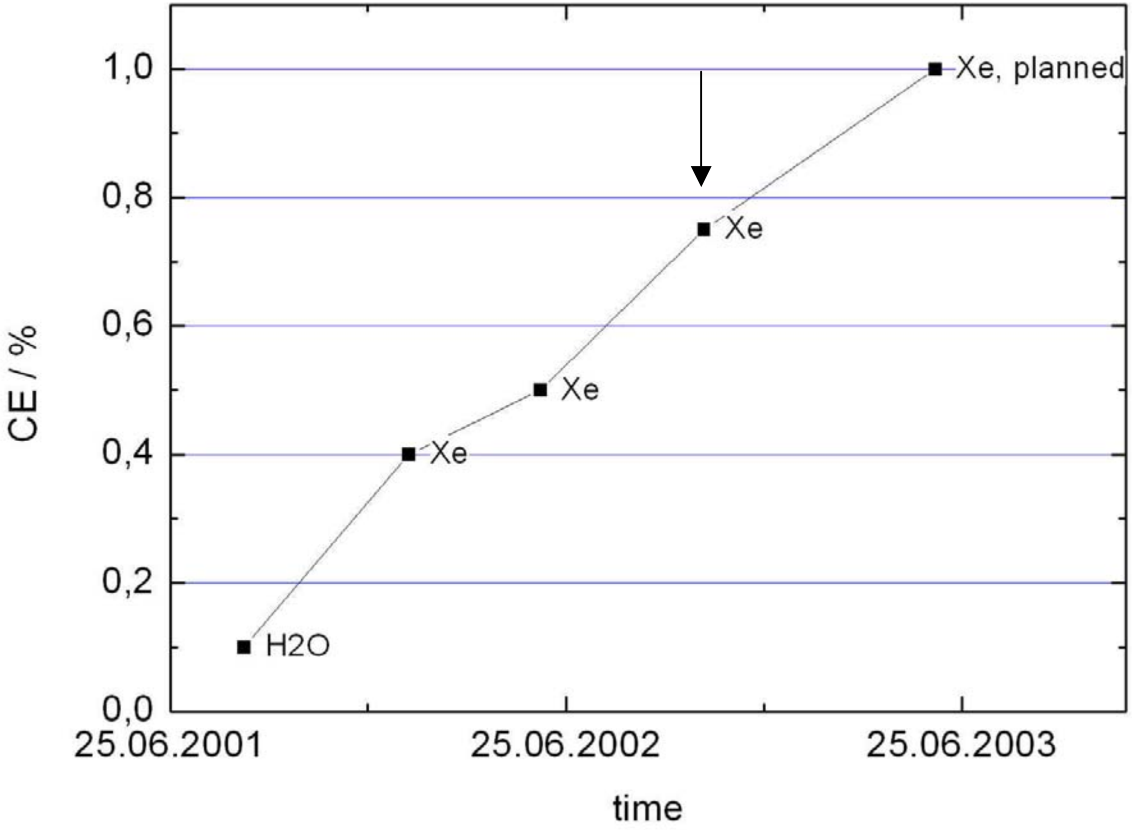
Variation of coupling parameters results in an increase of efficiency of more than 25%

The highest efficiency is achieved outside the tightest focus



Taking light to new dimensions…

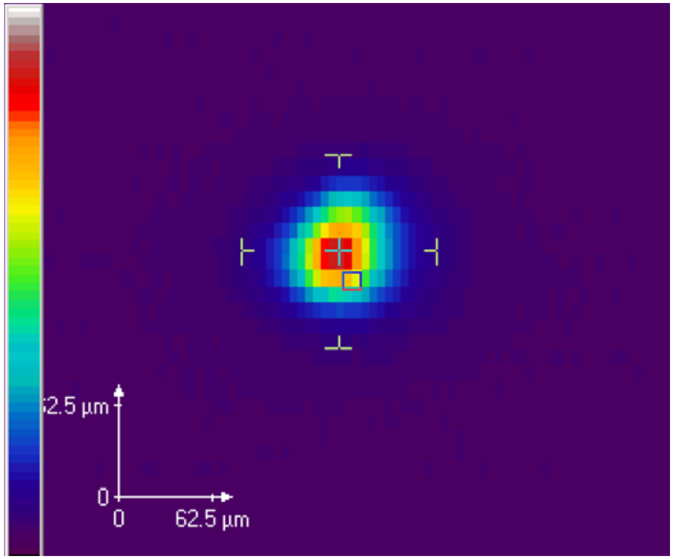
Historical trend of efficiency optimization



the highest conversion efficiency today is 0.75%

Taking light to new dimensions…

EUV-source size & stability



EUV-Plasma dimensions

Single pulse (test facility)

Laser beam direction: 46 µm (FWHM)

Xe-target direction: 55 µm (FWHM)

spatial stability

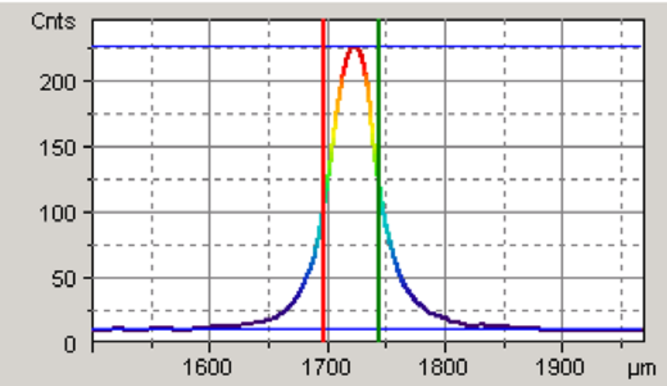
Laser beam direction : σ = 28 µm

Xe-target direction : σ = 3 µm

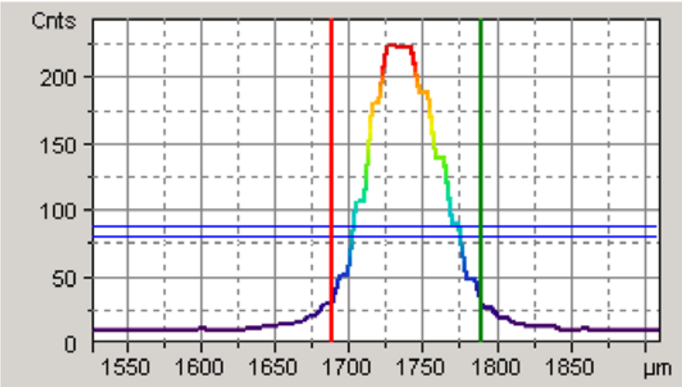
temporal stability

EUV-emission fluctuations : σ = 16 %

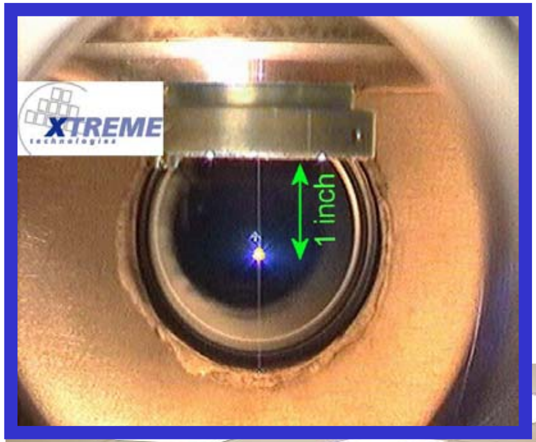
Horizontal Cross Section



Vertical Cross Section

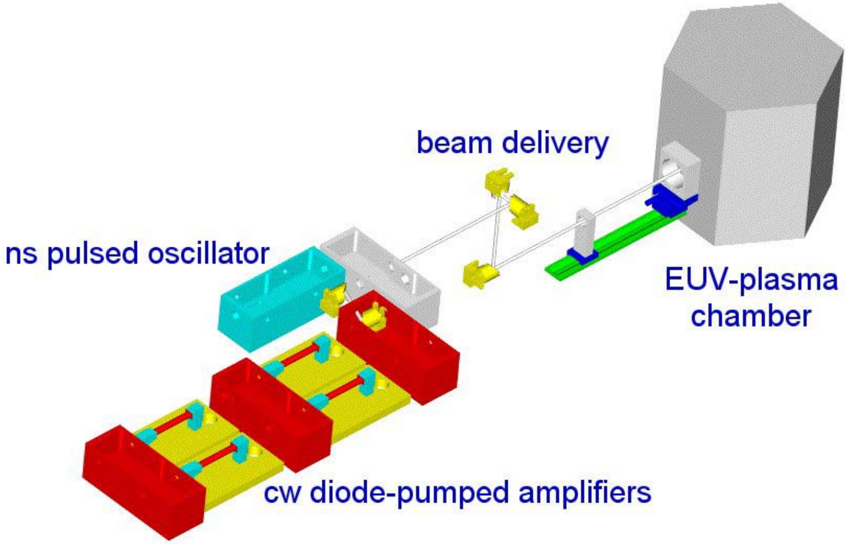


LPP high-power facility, Xe-target

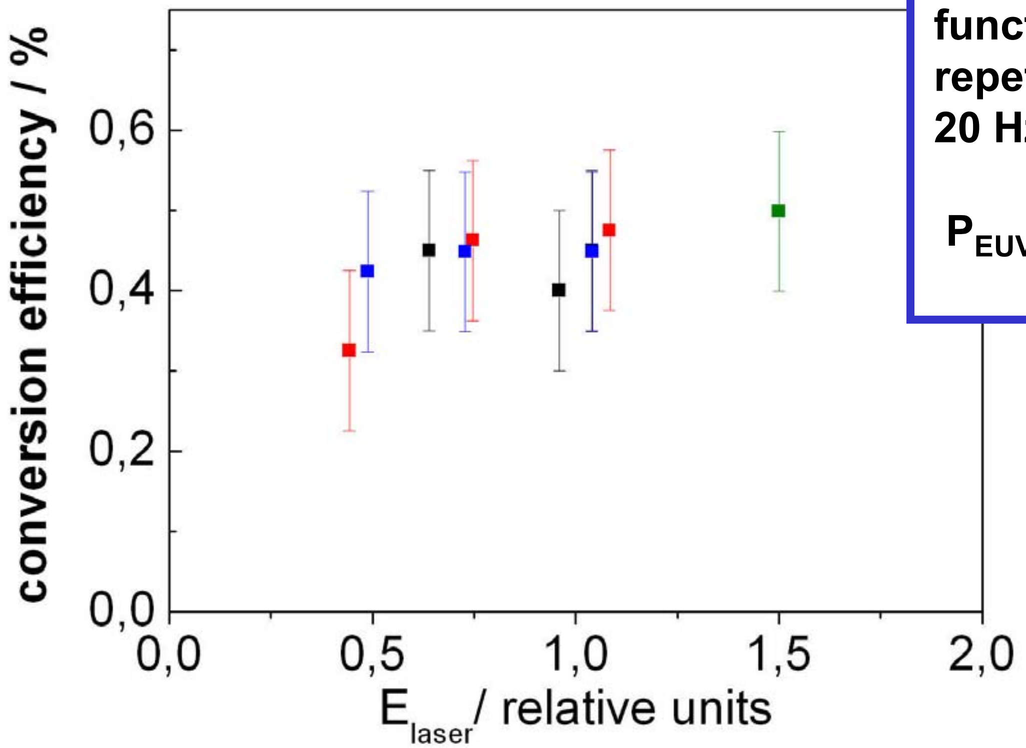


Laser parameters

Repetition frequency / kHz	laser power / W	Beam quality M^2
3.3	300	3.5
5	350	3.5
10	400	3.5



EUV conversion efficiency and in-band power



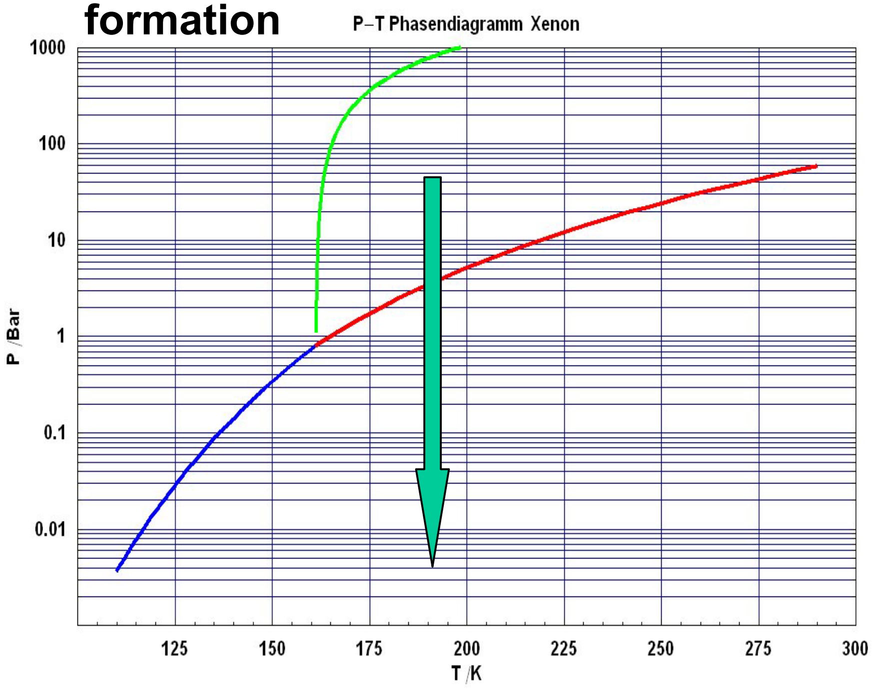
Maximum conversion efficiency as a function of laser pulse energy at repetition rates between 20 Hz – 3300 Hz (different colors)

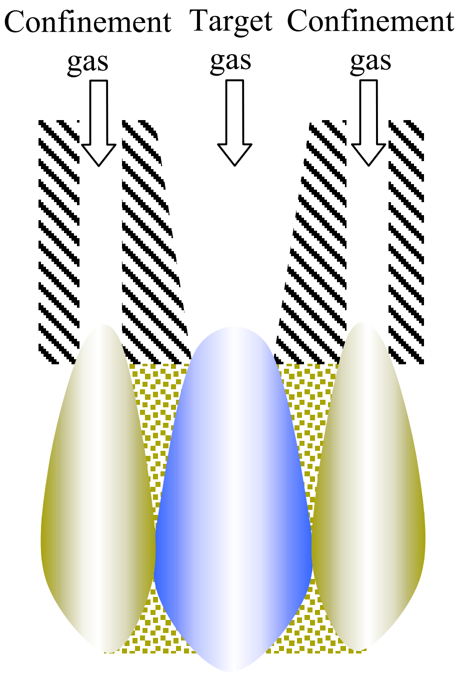
P_{EUV} (in 2π) = 1.5 W
(300 W laser at 3.3 kHz)

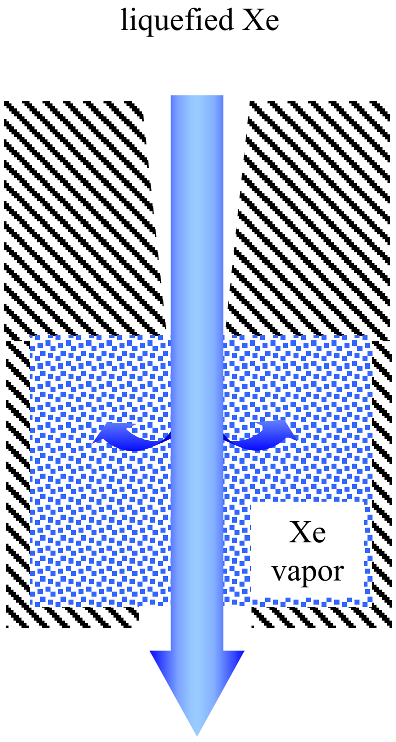
At the high power facility a peak conversion efficiency of 0.5 % in 2 % bandwidth and 2π sr was achieved at repetition rates up to 3.3 kHz (optimization identical to the low power facility NOT implemented yet)

2-nd generation nozzles

- **Because of the high Xe-vapor pressure at the operation point, the target leaves the nozzle in a highly instable condition**
- **Supplying the immediate exit region with a background pressure of the order of the vapor pressure (like double gas puff) should improve the stability dramatically**
- **The region of the background pressure might be long enough to support droplet formation**

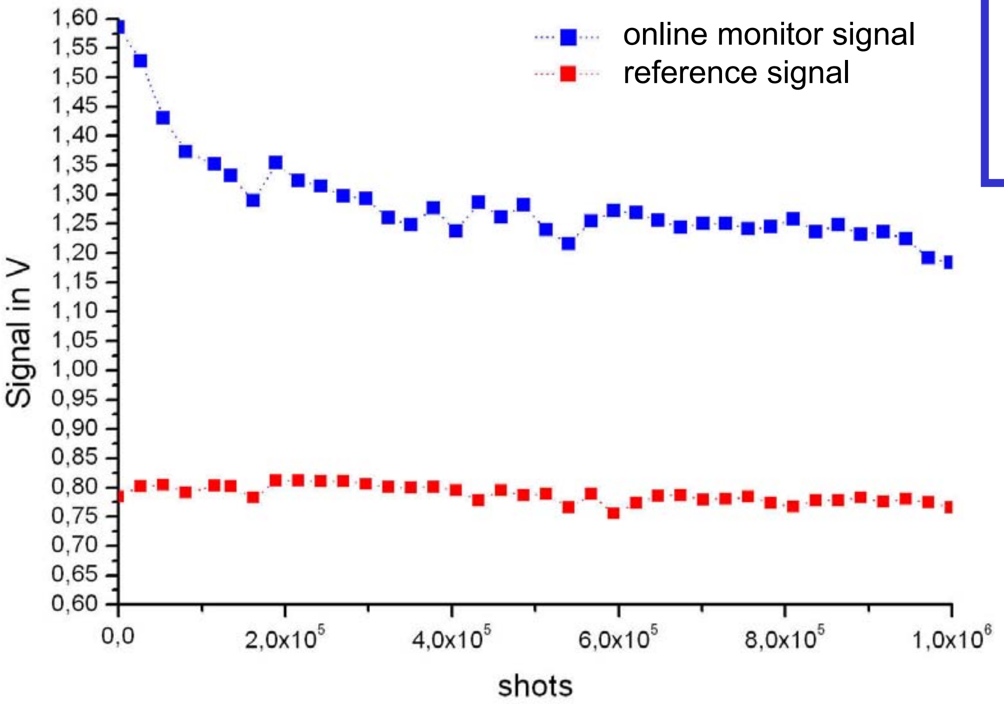






Taking light to new dimensions…

Online measurement of EUV-mirror reflectivity

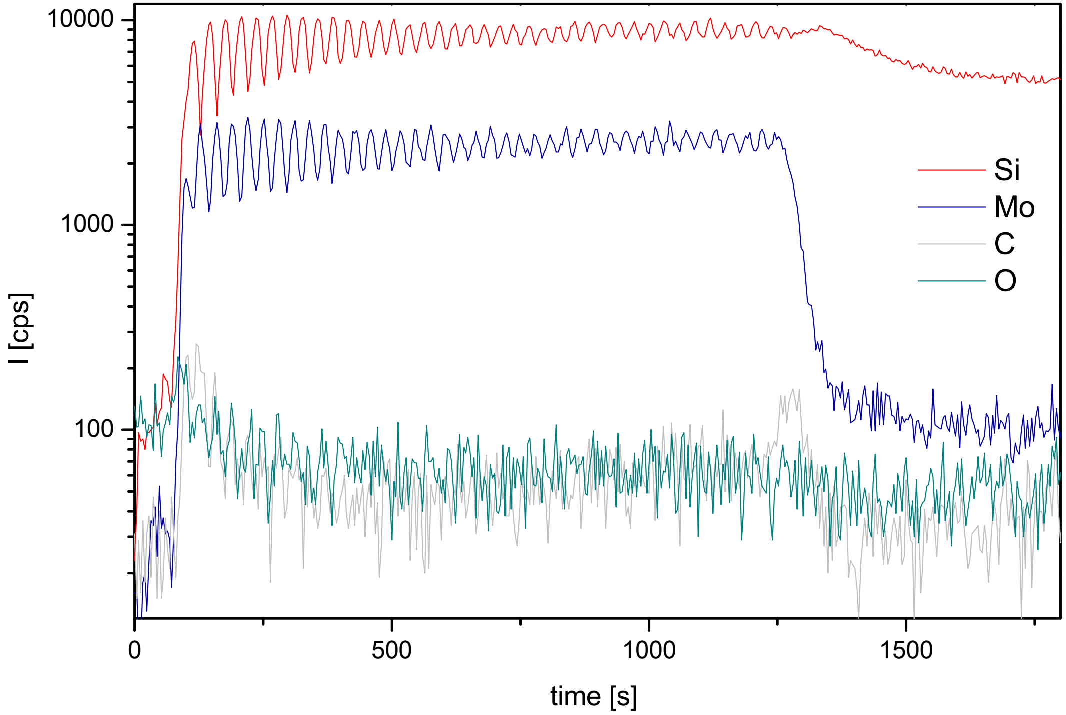


mirror:	**MoSi multi layer**
laser energy:	**30 mJ**
EUV energy:	**30 μJ (2 π sr)**
Target:	**H_2O**

- **The reflectivity drops about 20% within 100 000 shots and stays relatively constant up to at least 1 million shots**
- **For high power sources (30 W EUV in 2π sr) the total scale corresponds to 10 000 pulses, i.e. 20 % degradation after 1 000 pulses**

Analysis of the exposed mirror

mirror (witness plates) : MoSi multi-layer (40 layer pairs)



SNMS depth profile and XPS surface analysis

← SNMS-intensities via sputtertime

- **All multilayer pairs are present after exposure**
- **The reflectivity decrease is caused by Carbon deposition (XPS analysis)**

LPP EUVL source – summary

Summary of Xenon results

- A conversion efficiency (in-band) of 0.75% was achieved
- The in-band source diameter is about 50 microns (FWHM)
- The source was operated with a 300 W, 3.3 kHz Laser, which is well adopted to EUV-generation
- Maximum values of in-band EUV-power of 1.5 W achieved
- The source stability of 16% sigma is caused by target instabilities

Summary of debris results

- The lifetime (10 % reflectivity decrease) without debris mitigation means is expected to be in the order of 1 000 pulses for high power EUV sources
- The reflectivity drop is caused by carbon deposition

LPP EUVL source – outlook

Source stabilty

- **Improvement of the directional stability of the Xe-target**

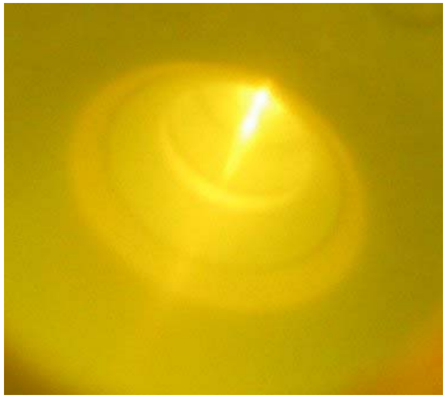
  ⇒ sigma < 5% is expected within the next half-year

Efficiency

- **Optimization of the plasma conditions ⇒ an in-band CE of ~1% is expected**

Laser power scaling

- **Upgrade to 2000 W average power in Q2 / 2003**



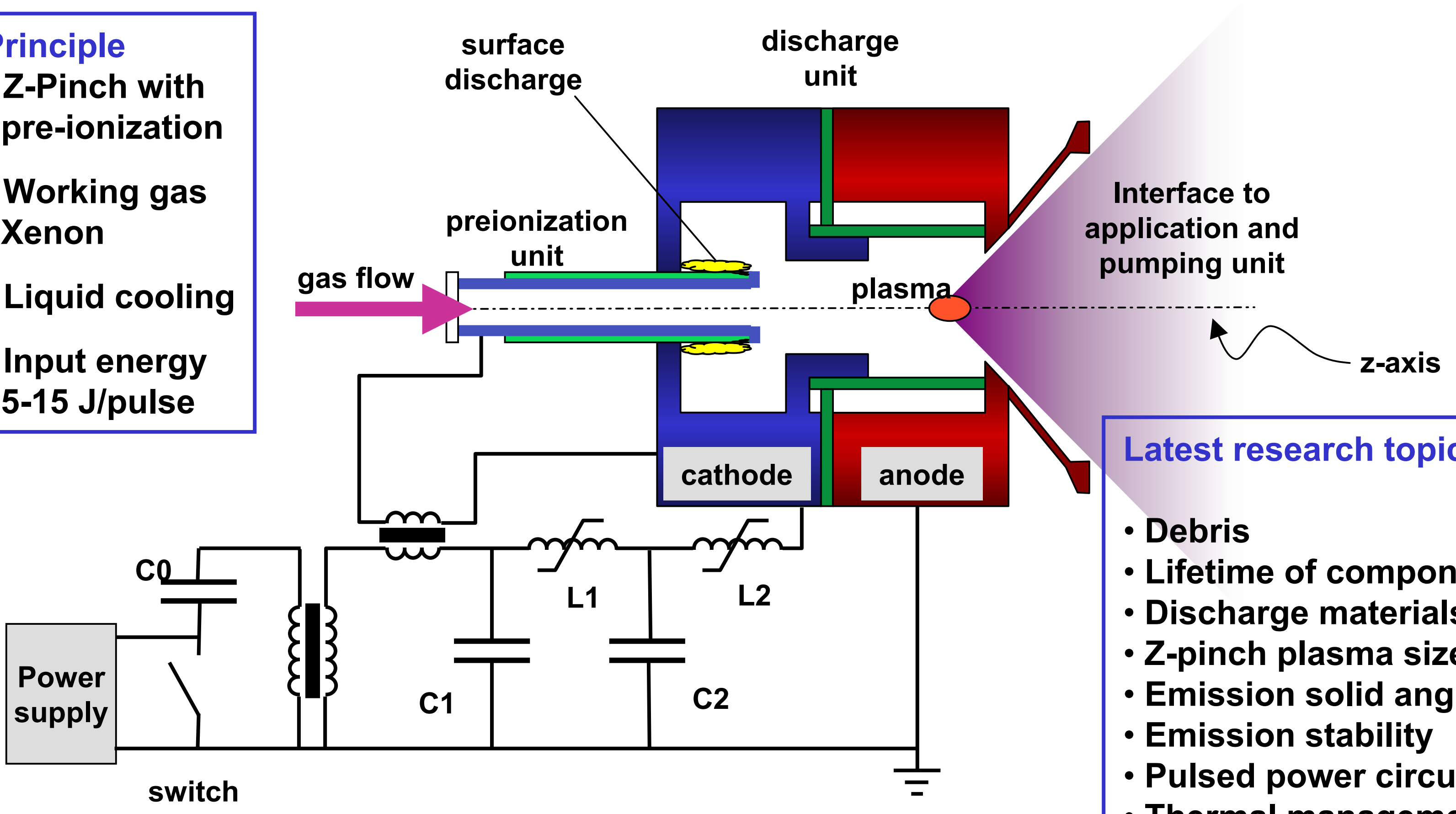
EUV-source power

- **~10 W EUV-inband power by in Q3 / 2003**

Gas Discharge Produced Plasma Z-Pinch source

Principle

- **Z-Pinch with pre-ionization**
- **Working gas Xenon**
- **Liquid cooling**
- **Input energy 5-15 J/pulse**



Latest research topics

- **Debris**
- **Lifetime of components**
- **Discharge materials**
- **Z-pinch plasma size**
- **Emission solid angle**
- **Emission stability**
- **Pulsed power circuit**
- **Thermal management**

Gas discharge produced EUV source prototypes

7 GDPP EUV sources have been built at XTREME technologies

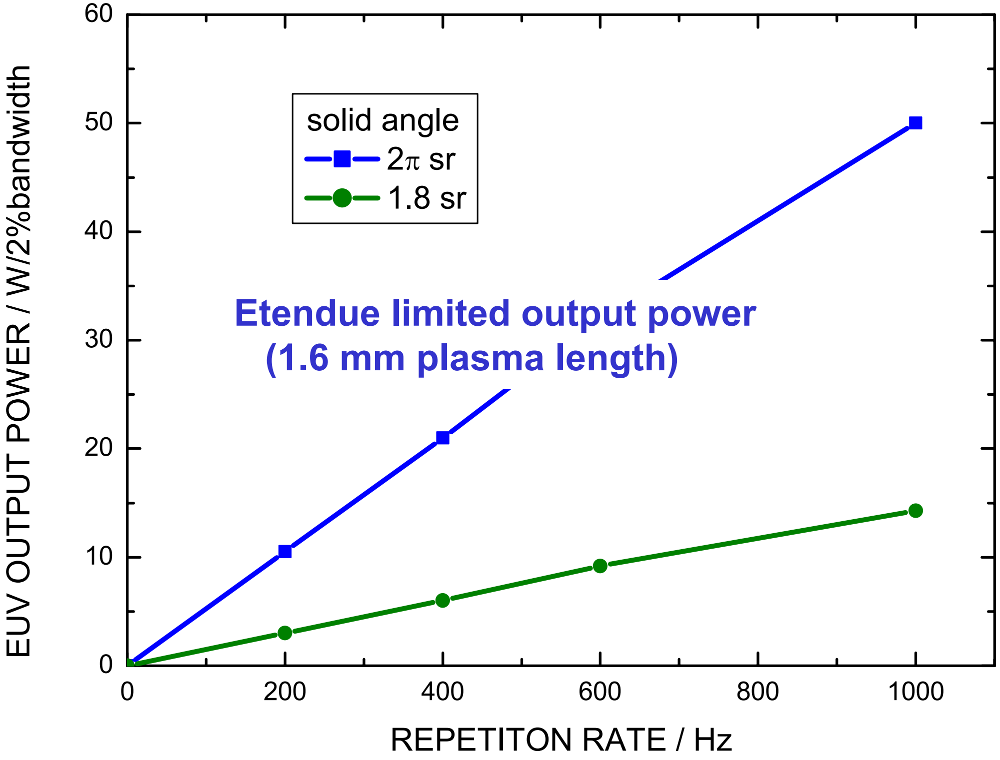
Taking light to new dimensions…

Micro Exposure Tool (MET) source

Beam line view

Rear side

GDPP EUV source – Power and conversion efficiency



Etendue limited output power (1.6 mm plasma length)

50 W power in 2π sr (etendue limited)

14 W power into 1.8 sr (etendue limited)

6.9 W in intermediate focus (no spectral purity filter)

5.5 W in intermediate focus (with spectral purity filter)

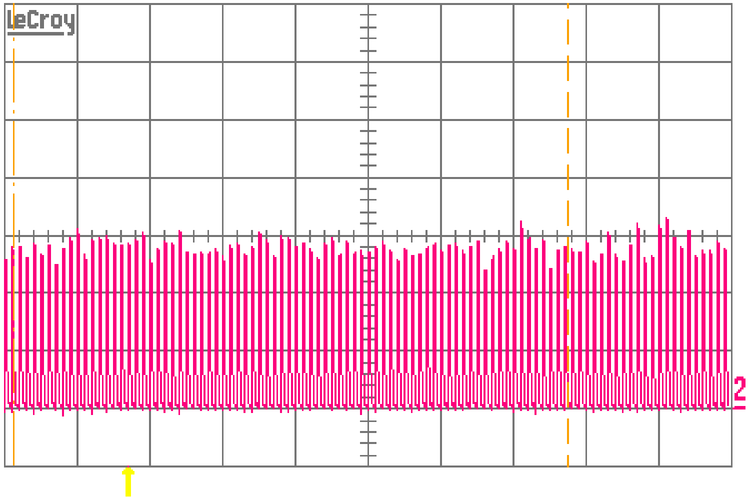
Conversion efficiency (EUV output in 2π sr /stored electrical energy) : 0.55 %

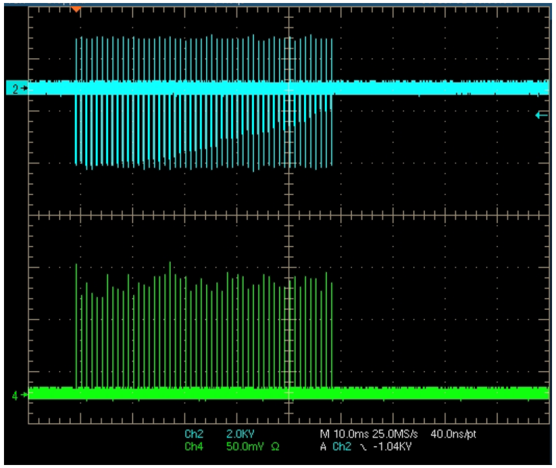
Intrinsic conversion efficiency (EUV output in 2π sr/energy deposited in plasma) : 1.2 %

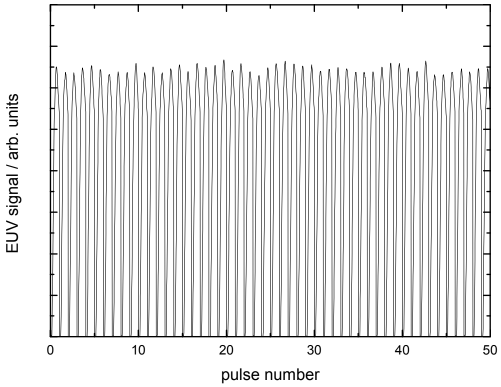
XTREME technologies

Taking light to new dimensions…

Pulse to Pulse Repeatability







Pulse to pulse repeatability: 1.5% ... 5 % (sigma)

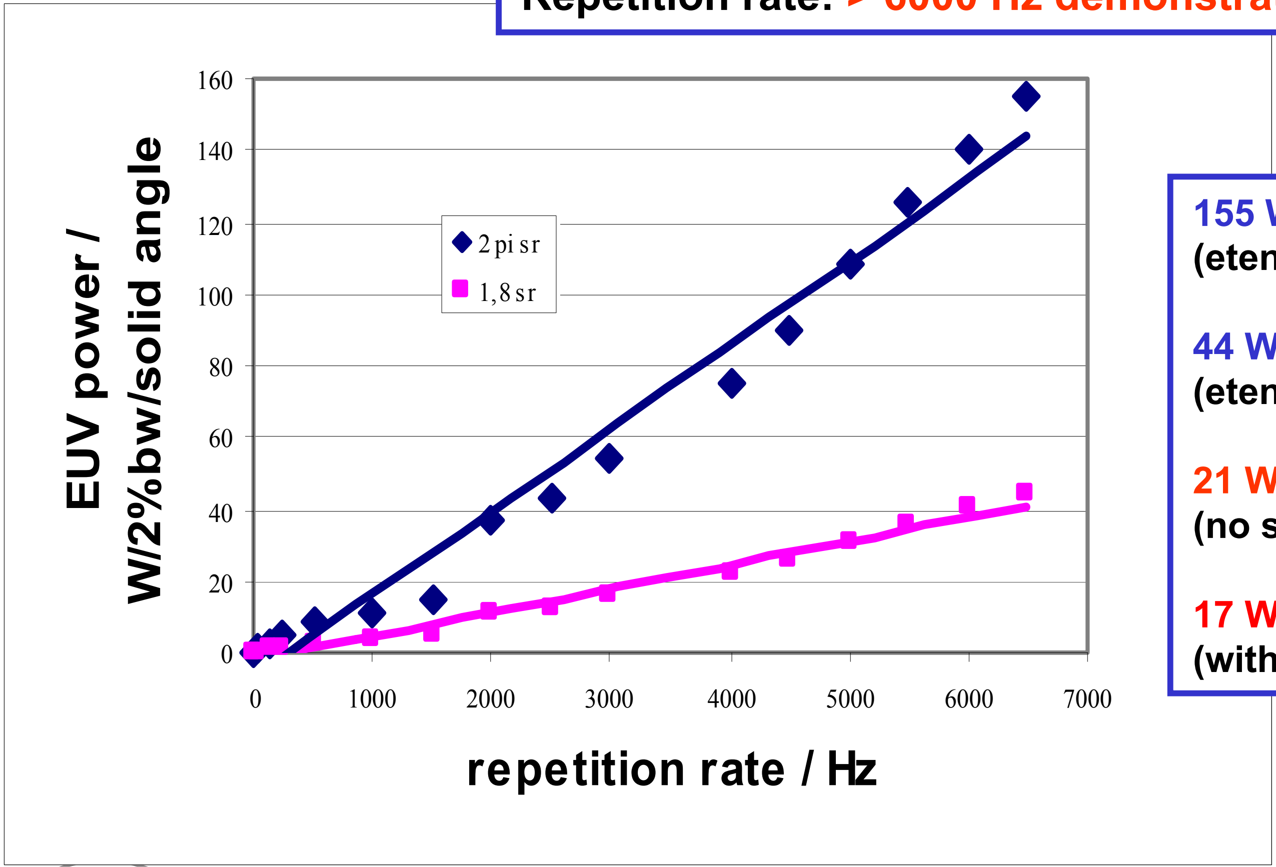
No active feedback
HV=constant mode

XTREME technologies

Taking light to new dimensions…

Repetition frequency

Repetition rate: > 6000 Hz demonstrated in burst operation



155 W power in 2π sr
(etendue limited)

44 W power into 1.8 sr
(etendue limited)

21 W in intermediate focus
(no spectral purity filter)

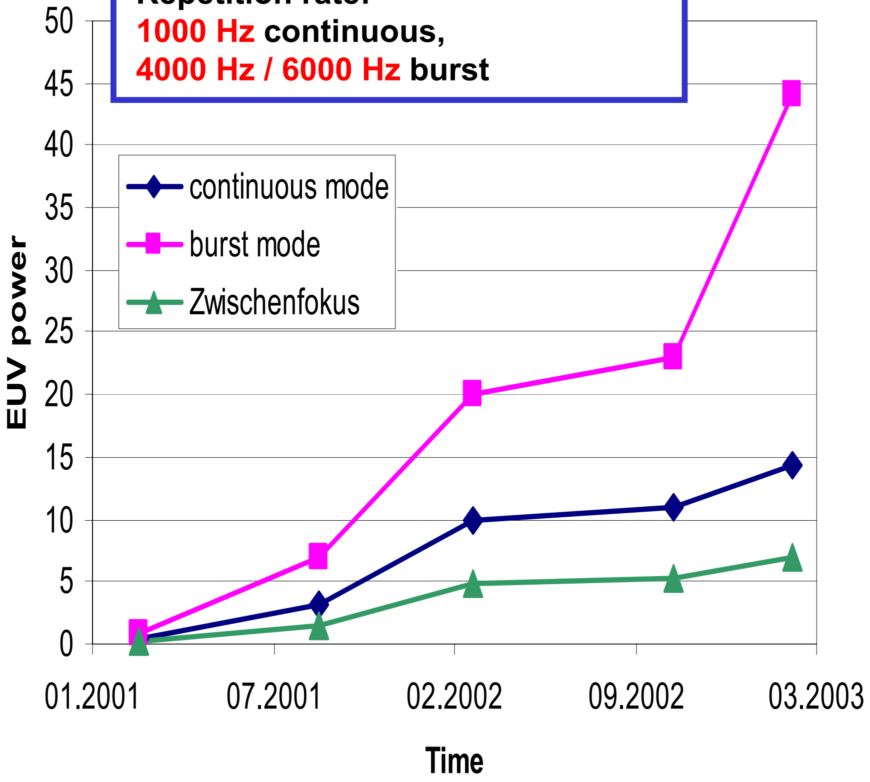
17 W in intermediate focus
(with spectral purity filter)

Taking light to new dimensions…

XTREME technologies – Results Z-Pinch

Collectable EUV power - history

Repetition rate:
1000 Hz continuous,
4000 Hz / 6000 Hz burst



Improvement of power: Cooling concepts

Modeling for cooling concept optimization

Variation of geometry and material properties

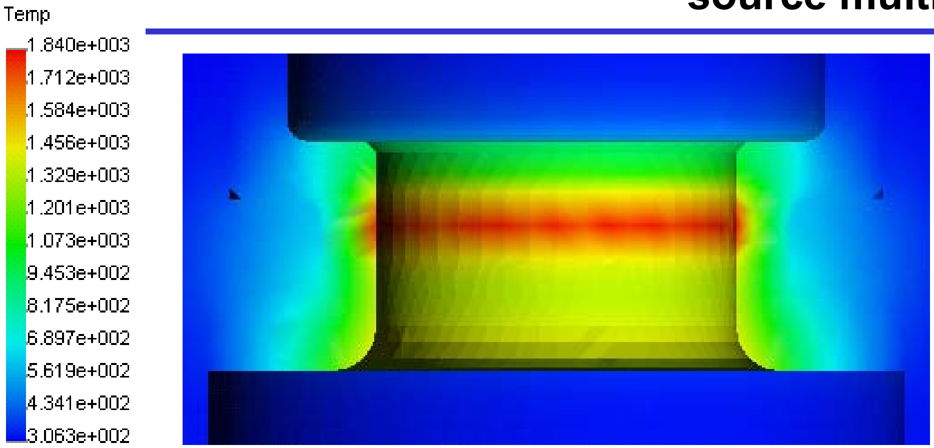
Requirements:
Peak temperature on surface below 2700 K
(200 K below melting temperature of Molybdenum)

Conventional:
10 kW input power possible

Simulation of new concept:
25 kW input power
(porous metal cooling)

Production requirements:
90 kW input power
(innovative cooling, source multiplexing)

Example:
Z-Pinch setup



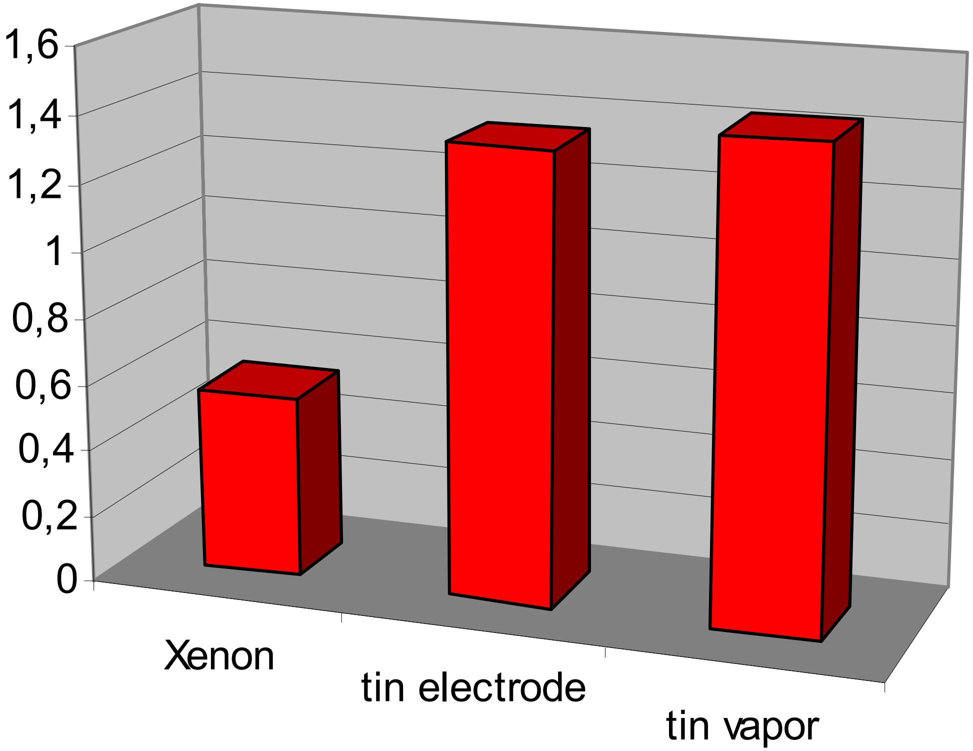
Taking light to new dimensions…

Improvement of power and conversion efficiency

Alternative target materials

Improvement of conversion efficiency by using of tin (factor 2.5 ... 3)

New challenge:
Target material handling

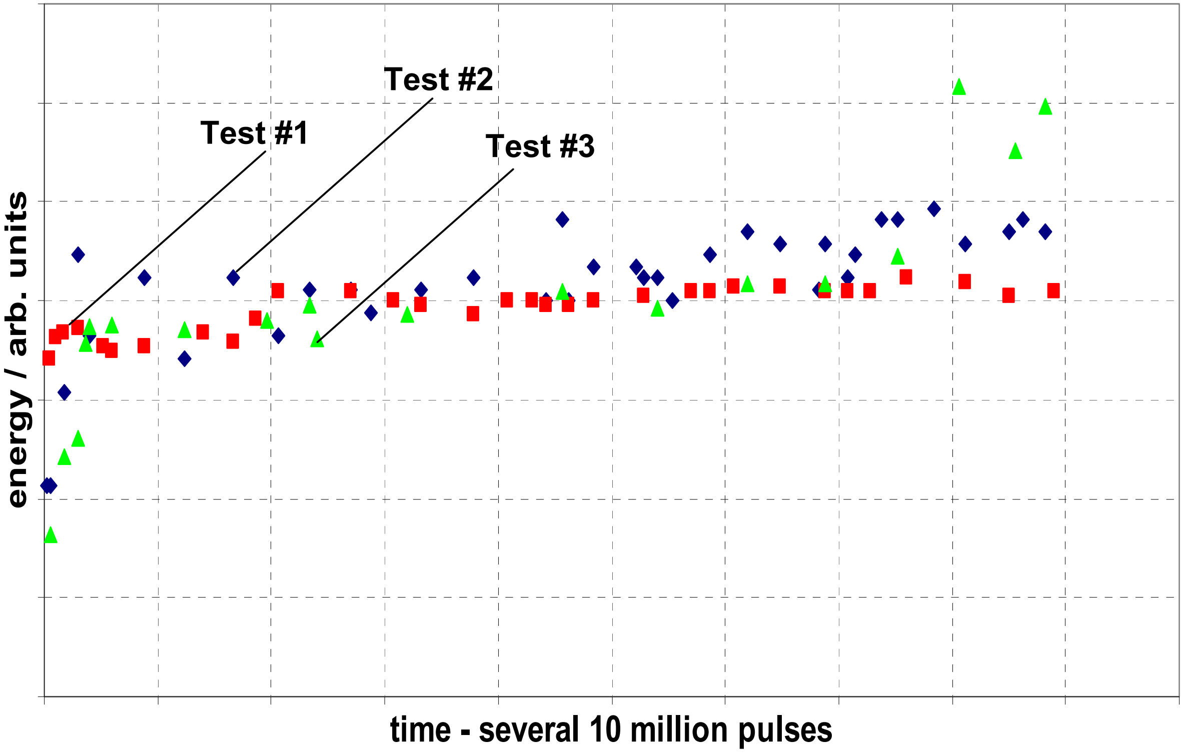


Taking light to new dimensions…

EUV power – Longterm tests

Nearly constant EUV power during longterm tests

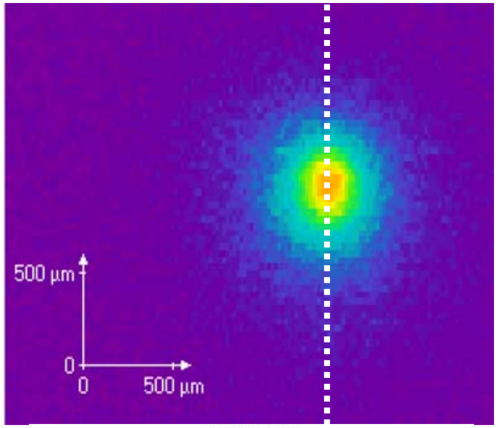
No active feedback (HV = constant mode)

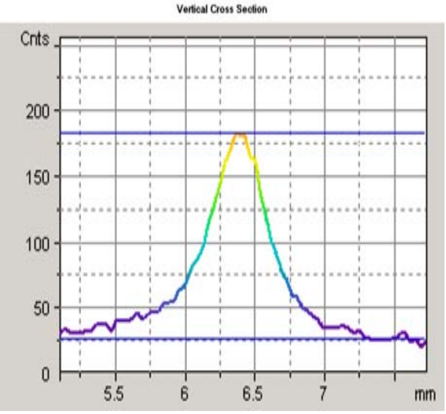


Taking light to new dimensions…

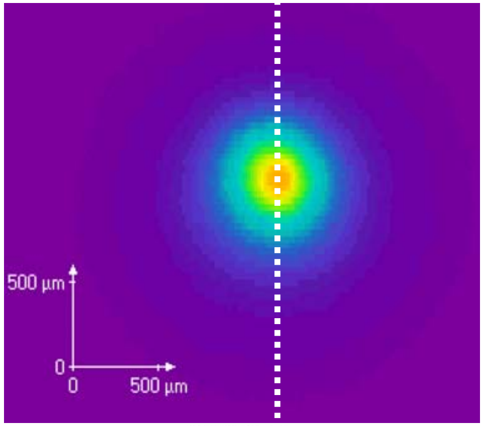
Etendue of source

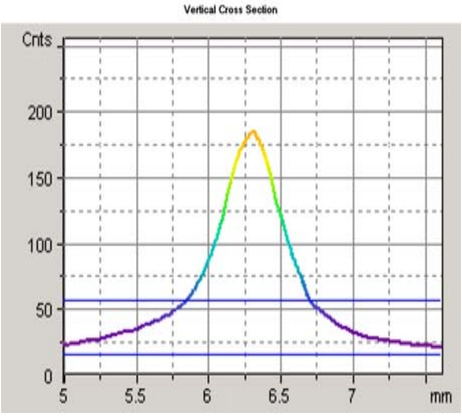
Single pulse





200 pulses average





Diameter

Average over 200 pulses

0.5 mm (FWHM)

Etendue in 1.8 sr collection angle:

1.4 mm^2 sr

Length

Average over 200 pulses

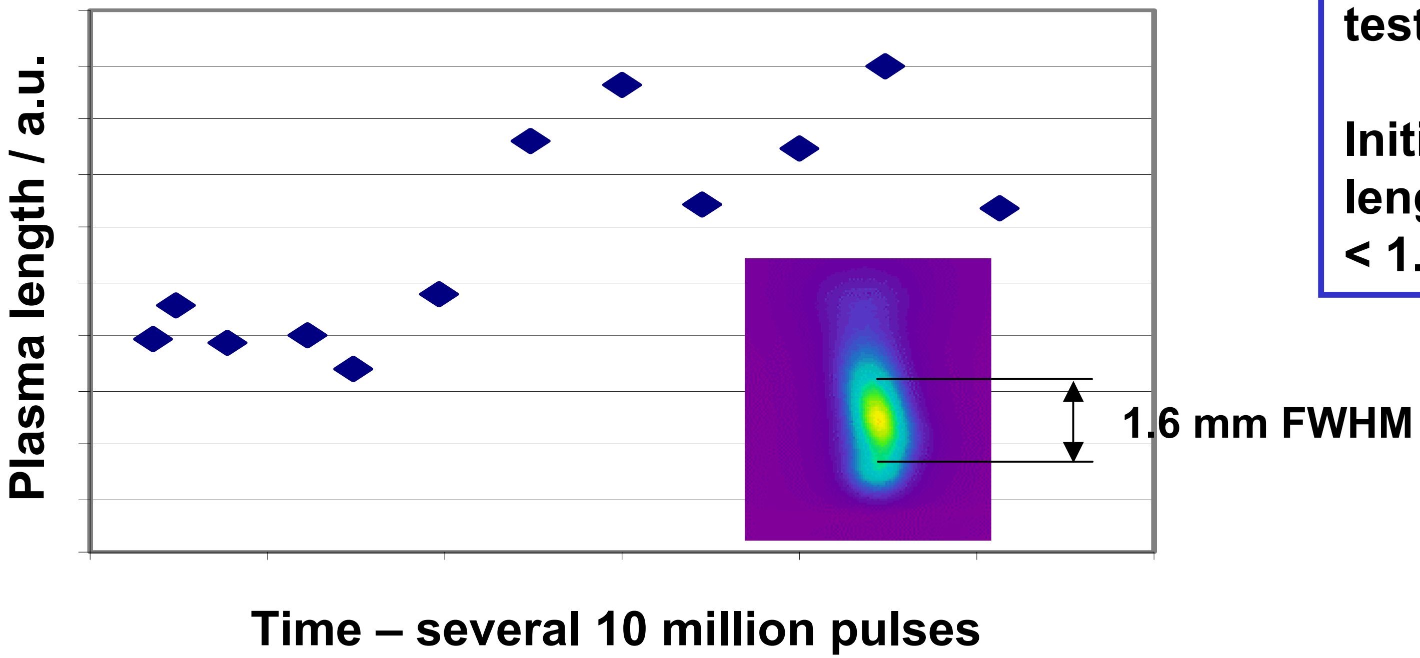
1.6 ... 4.0 mm (FWHM) tunable

Position

Center of gravity
Pointing stability 50 µm
Standard deviation < 6 % of diameter (1/e²)

Taking light to new dimensions…

EUV plasma size – Longterm tests



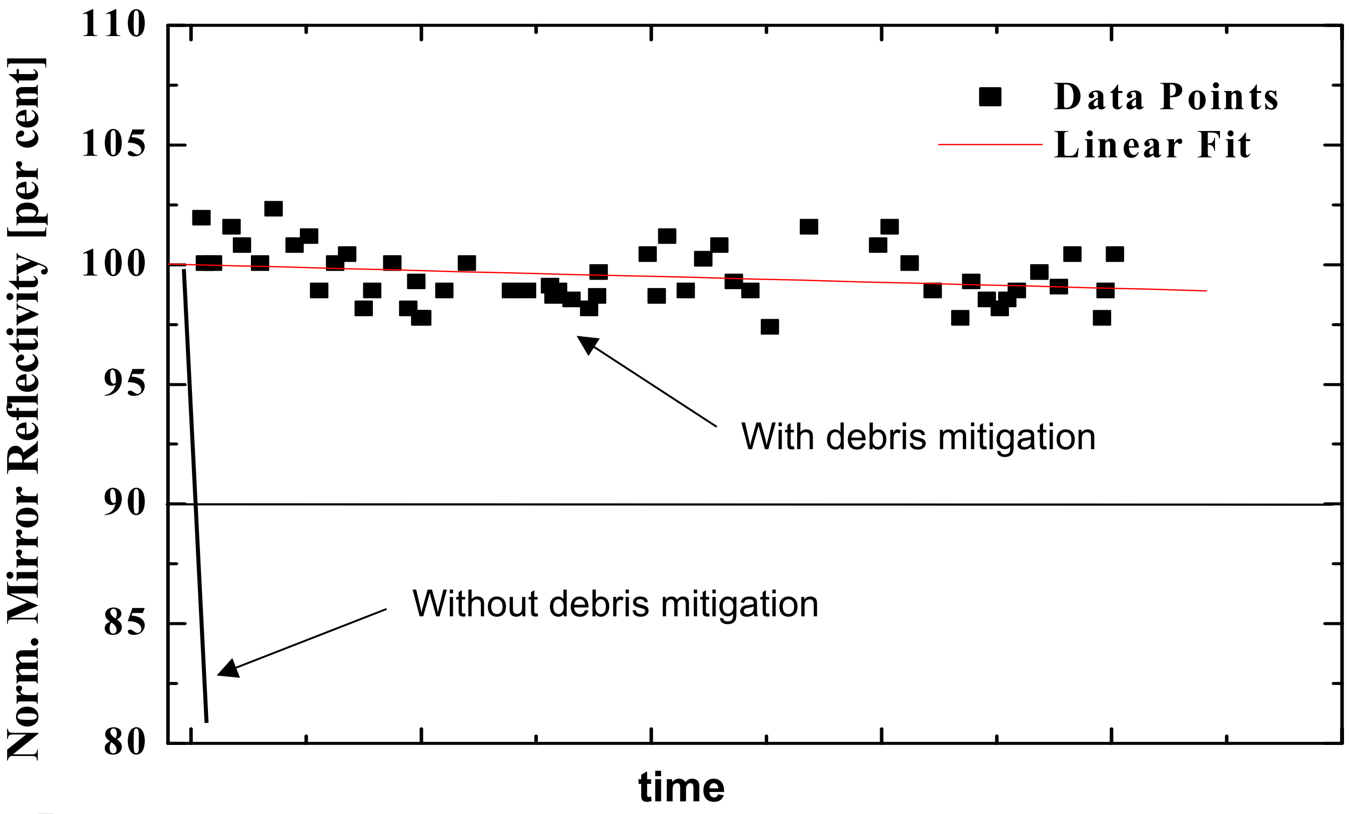
Length increases during longterm tests

Initial plasma length tunable < 1.6 ... > 4.0 mm

Debris Mitigation

Measurements with grazing incidence optics

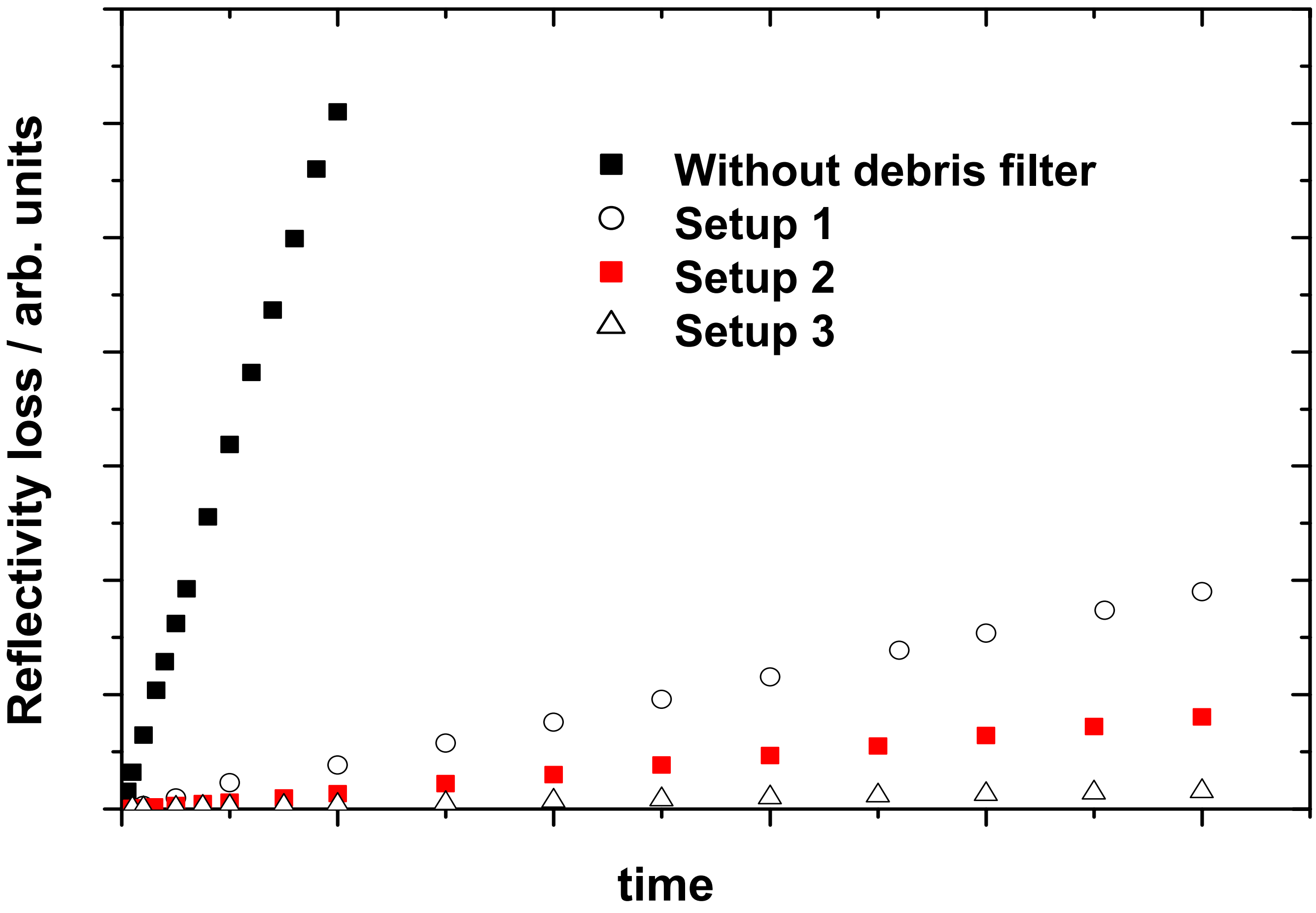
Application of Debris mitigation tools



With debris mitigation

Without debris mitigation

Debris Mitigation – Reflectivity loss



GDPP EUV source - summary

- **EUV output power 50 W in 2π sr / 14 W in 1.8 sr continuous, 5.5 W in intermediate focus with spectral purity filter**

- **EUV output power 155 W in 2π sr / 44 W in 1.8 sr burst mode, 17 W in intermediate focus with spectral purity filter**

- **Energy stability measured 1.5 ... 5 % (sigma)**

- **Plasma size diameter 1.3 x length 1.6 ... 4.0 mm (tunable)**

- **Conversion efficiency 0.55 % /2π sr / 2% bw**

- **Intrinsic conversion efficiency 1.2 % /2π sr / 2% bw**

- **Electrical input energy < 10 J / pulse**

- **Emission angle ≈ 2 srad (=45° half opening angle)**

- **Reduction of debris by several orders of magnitude**

Can we meet production requirements – GDPP

		today	**today / burst**	**power final**	**CE final**
		typical	**best ever**		
diss. Power / W		**8700**	**27000**	**90000**	**30000**
target		Xe	Xe	Xe	Sn?
CE / %		0,55%	0,55%	0,70%	3%
inband 2Pi / W		47,85	148,5	630	900
	solid angle / 2Pi	0,29	0,29	0,40	0,40
	ave. Reflectivity	70%	70%	70%	70%
total coll. Eff.					
	coll. Eff. w/o SPF	0,14	0,14	0,25	0,25
	coll. Eff. w SPF	0,12	0,12	0,20	0,20
inband i.f. / W					
	inband i.f. w/o SPF / W	**6,91**	**21,45**	**158,00**	**225,72**
	inband i.f. w SPF / W	**5,53**	**17,16**	**126,40**	**180,57**

XTREME technologies

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Can we meet production requirements – LPP

		today typical	**today best ever**	**laser final**	**CE final**
diss. Power / W		**300**	**400**	**15000**	**15000**
target		Xe	Xe	Xe	Sn?
CE / %		0,50%	0,75%	1%	3%
inband 2Pi / W		1,5	3	150	450
	solid angle / 2Pi	1	1	1	1
	ave. Reflectivity	45%	45%	45%	45%
total coll. Eff.					
	coll. Eff. w/o SPF	0,405	0,405	0,405	0,405
	coll. Eff. w SPF	0,324	0,324	0,324	0,324
inband i.f. / W					
	inband i.f. w/o SPF / W	**0,6075**	**1,215**	**60,75**	**182,25**
	inband i.f. w SPF / W	**0,486**	**0,972**	**48,6**	**145,8**

EUV source power roadmap

Gas discharge produced plasma EUV source

Month/Year	03/2002	02/2003	06/2003	10/2003	06/2004	03/2006	2008
Power in 2 pi	35 W	50 W	100 W	150 W	200 W	400 W	800 W
Collectable Power in 1.8sr	10 W	14 W	28 W	43 W	57 W	114 W	318 W (2.5 sr)
Power in 2nd focus without SPF	4,8 W	6,7 W	13,5 W	21 W	28 W	55 W	154 W
Power in 2nd focus with SPF	3,8 W	5,4 W	11 W	16 W	21W	42 W	123 W

Laser produced plasma EUV source

Month/Year	03/2002	02/2003	06/2003	10/2003	06/2004	03/2006	2008
Power in 2 pi	0,2 W	1 W	1,5 W	10 W	20 W	130 W	385 W
Collectable Power in 2 pi sr	0,2 W	1 W	1,5 W	10 W	20 W	130 W	385 W
Power in 2nd focus without SPF	0,08 W	0,4 W	0,6 W	4 W	8 W	52 W	154 W
Power in 2nd focus with SPF	0,06 W	0,32 W	0,48 W	3,2 W	6,4 W	42 W	123 W

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