Advanced INNOSLAB Solid-state-lasers for the generation of bright XUV/EUV-radiation

Fraunhofer Institute for Laser Technology (ILT)

Peter Loosen
Marco Höfer, Dominik Esser, Henrik Sipma, Raphael Kasemann, Hans-Dieter Hoffmann

2010 International Workshop on Extreme Ultraviolet Sources
November 13-15, 2010
University College Dublin ▪ Dublin, Ireland

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Outline

Motivation
- XUV Generation

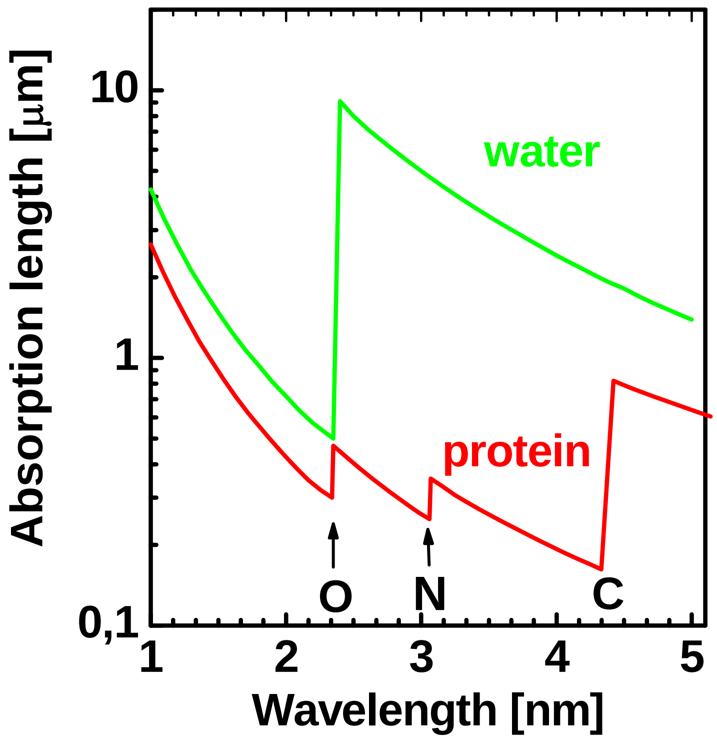
Requirements
- Power, Beam Quality, Pulse Duration

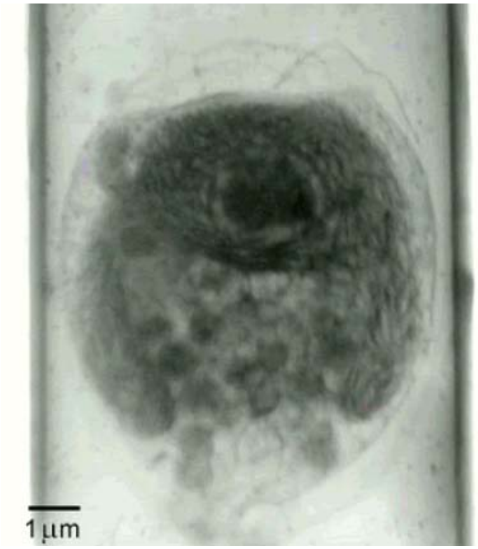
Configuration
- Diode Seeder
- Regenerative Amplifier
- INNOSLAB pre- and power Amplifier
- Polarization Combining

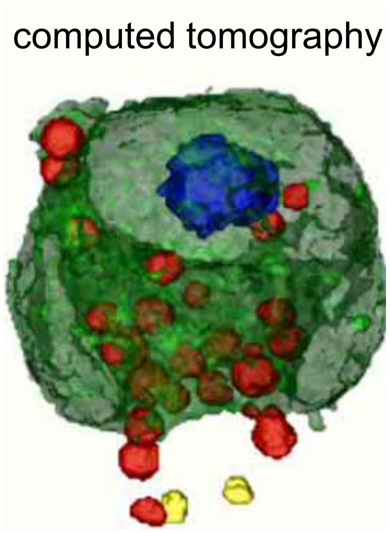
Results
- Power, Energy, Beam Quality, etc.

Motivation

- Water window (**2.4 – 4.4 nm**) is of interest for x-ray microscopy
- Absorption of the surrounding water is smaller than that of organic samples.







Pictures: BESSY, Schneider et al.

from: D. Weiss et al., Ultramicroscopy 84, (2000)

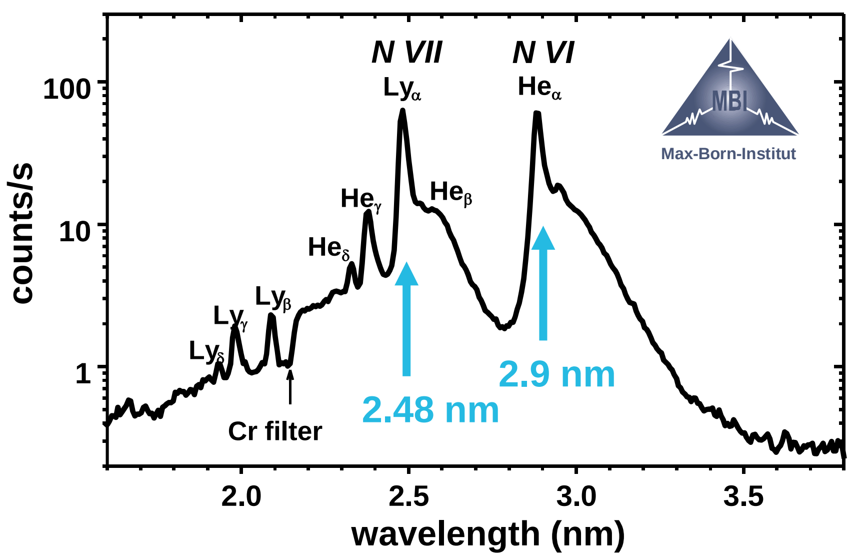
3d structure of frozen Algae

Motivation

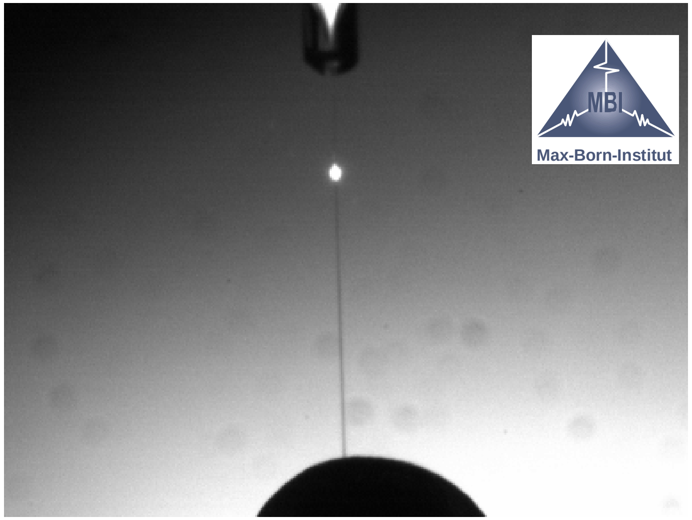
Benefit of **LPP** source in comparison to **DPP** source:

- highly efficiency generation of 2.48 nm and 2.9 nm
- high brightness of the XUV source (only 20 µm source diameter)

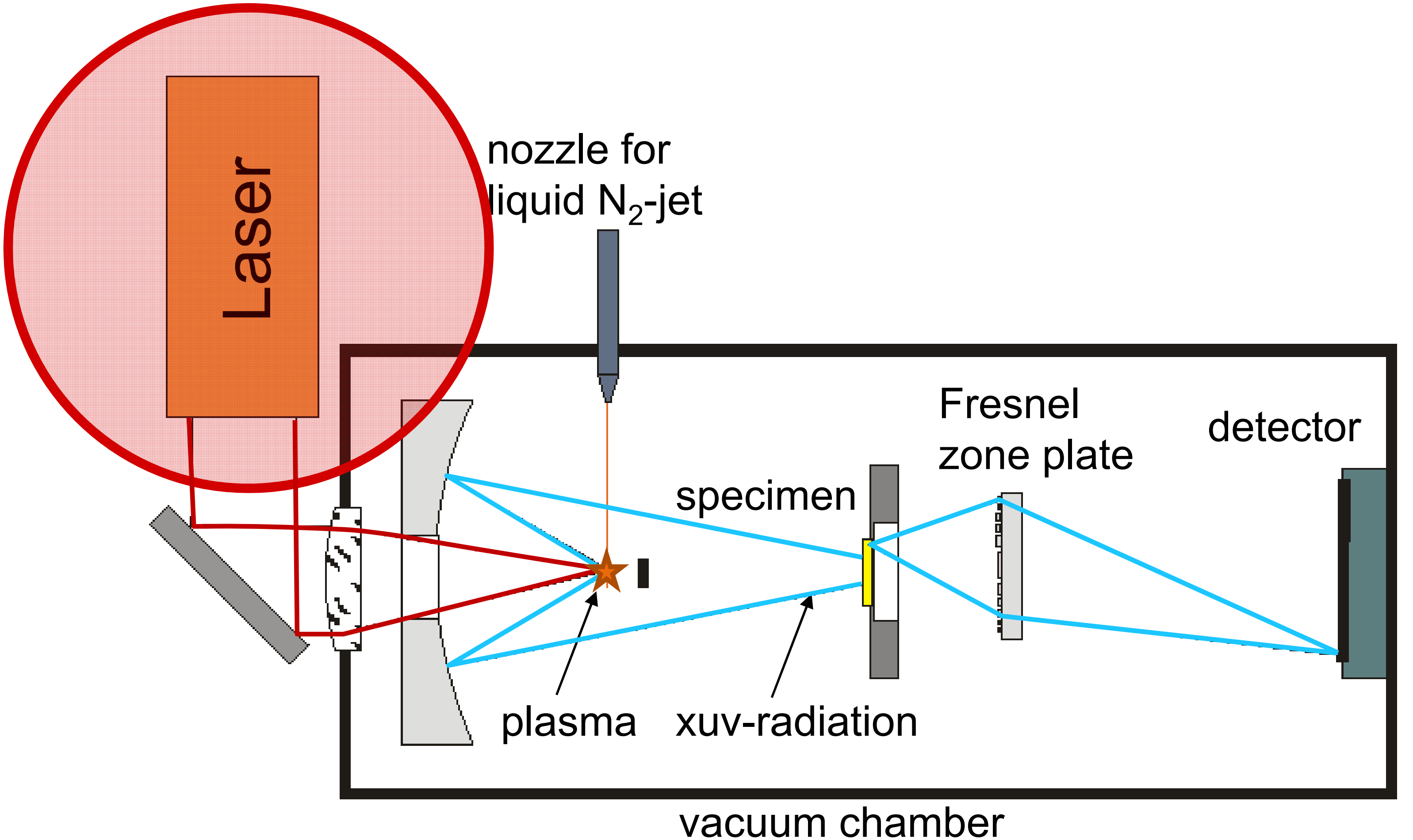
Emission spectrum of highly ionized nitrogen.



Nitrogen cryo jet laser plasma source.



Schematic view of a x-ray microscope



Evaluation of required laser parameters

Required XUV-wavelength („water window“):	$\lambda \approx 2{,}5$ nm
XUV-Photon energy:	$\varepsilon_{ph} \approx 500$ eV
Electron temperature for photon production :	$T_e \propto (I_L)^{4/9}$
Required laser intensity I_p @ 500 eV photon energy:	$2 \cdot 10^{12}$ W/cm^2
Power to achieve I_p (100 μm focal diameter):	150 MW
(20 μm focal diameter):	6 MW
High brightness of the XUV-spot required	$r_f < 100$ µm
Lower limit of focal diameter given by wavelength, f/D-number and beam quality (M^2)	$2r_f = M^2 \cdot \frac{4}{\pi} \cdot \frac{f}{D} \cdot \lambda$
Value for Nd:YAG-laser, f/D = 15 and max. beam quality	$r_f > 20 \mu m$
Upper pulse length limit (no plasma expansion in extend to 20 μm):	$\tau_p < 5$ ns

low exposure time -> high laser repetition rate,
limited by average power: > kHz

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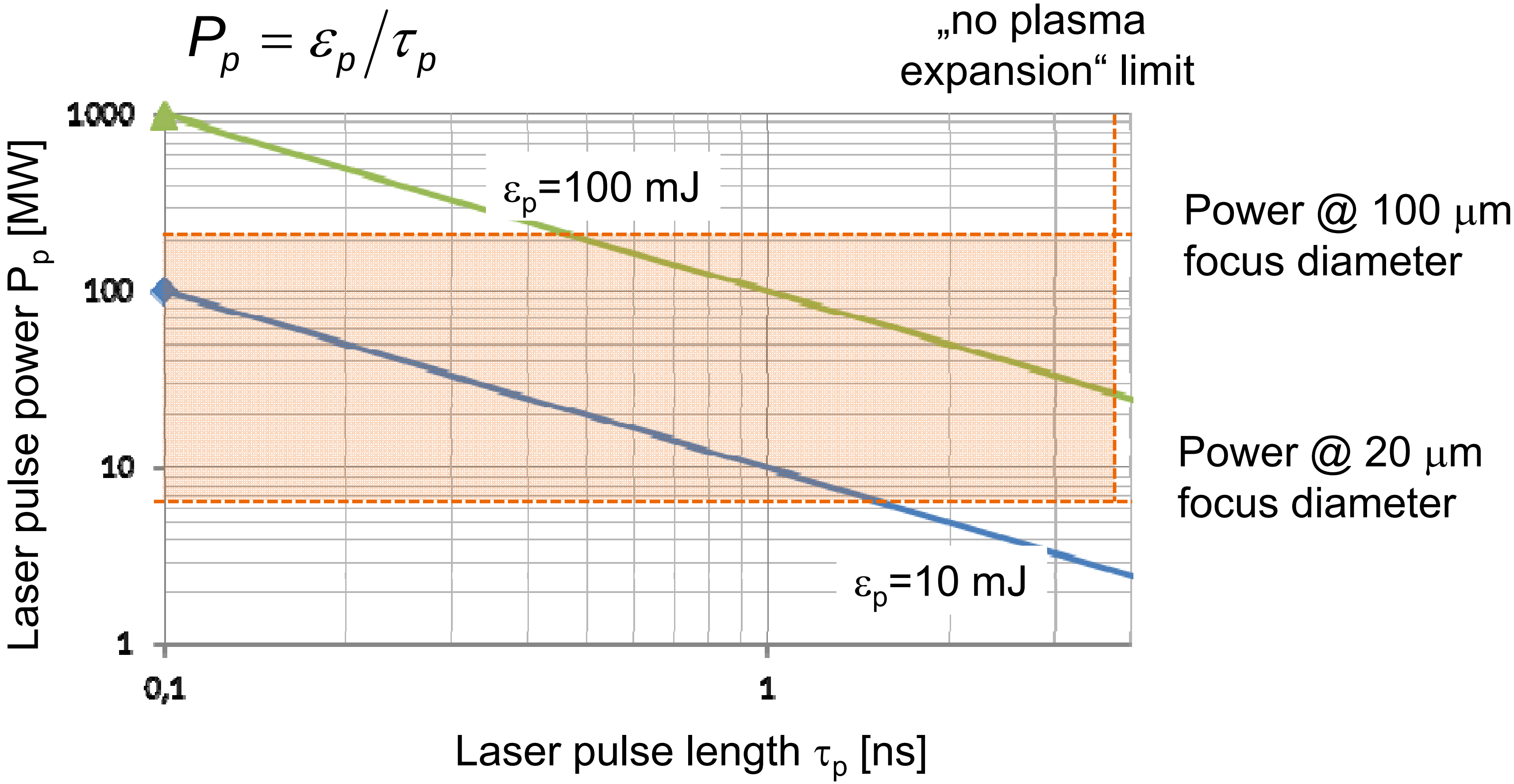
Laser parameter range: pulse length, energy and power



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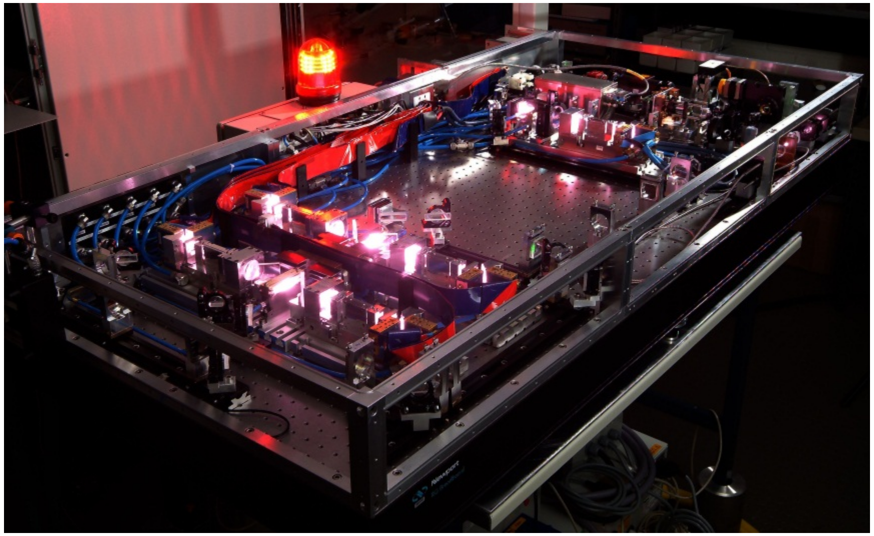
Laser design goals

Based on available base technology (solid-state Innoslab laser) a laser with the following parameters is specified:

wave length	1064 nm
pulse length	0,5 – 2 ns
pulse energy, E_{MP}	100 - 150 mJ
av. power	200 -300 W
rep. rate	2 kHz
laser power contrast ratio	> 500:1
M^2	< 2



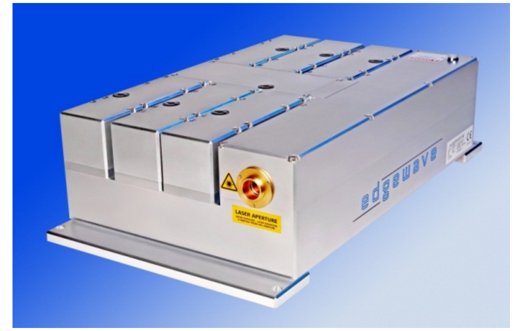
Contrast ratio = $E_{MP} / \sum E_{PP}$ (pp-pre pulses)

Laser with a combination of the required parameters (pulse energy and length, average power and repetition rate) are commercially not available.

Commercial systems

Commercially available solid-state lasers (for instance "Innoslab"- lasers of EDGEWAVE or "BrigthLigth" - lasers of JMAR) have:

- Operation: q-switch, MOPA, mode locking
- Continuously/pulsed pumped amplifier stages



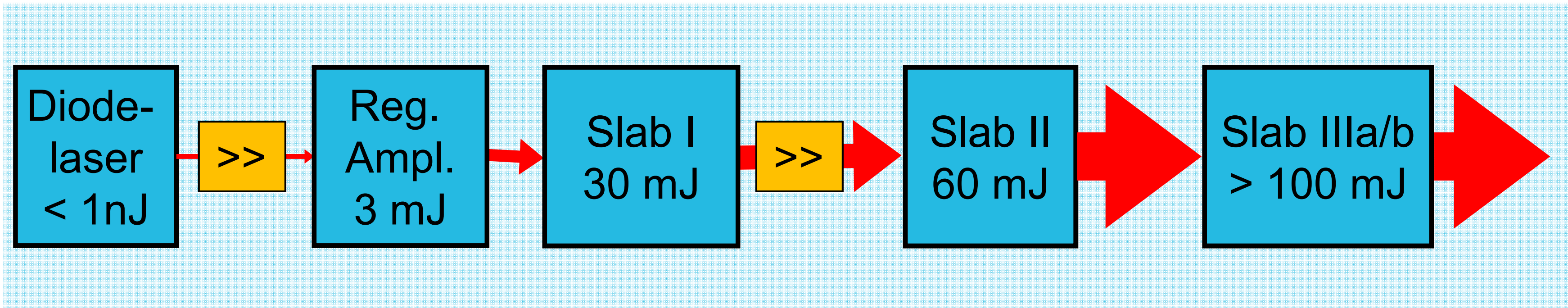
Edge-Wave, HD-series

Performance of such systems is partly near the desired values, but actually not yet sufficient with respect to pulse length, average power etc.:

Jmar, „BrigthLigth" series

Development and build-up of an oscillator-amplifier concept with parameters dedicated to the specific EUV-application is necessary

Principle set-up



Diode-laser seeder:
Rugged and stable concept, variable pulse length, pulse energy < 1 nJ

Regenerative Amplifier:

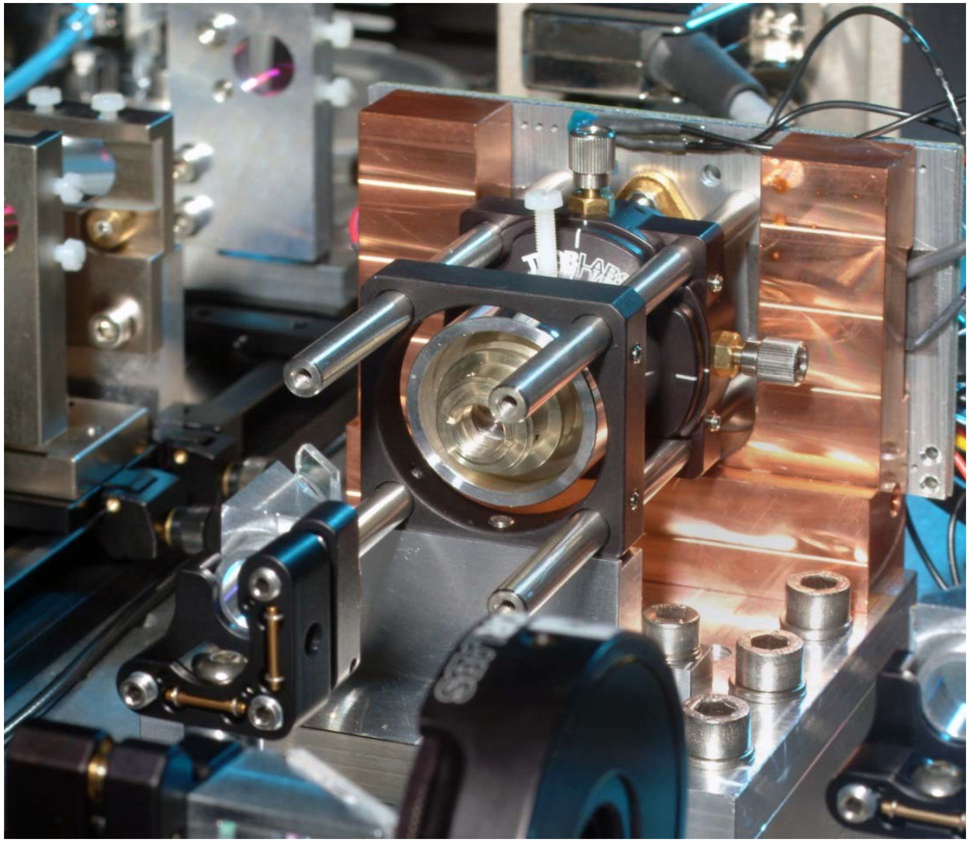
- Standard rod shaped active medium,
- Faraday isolator for protection of seed laser

Slab shaped amplifiers:

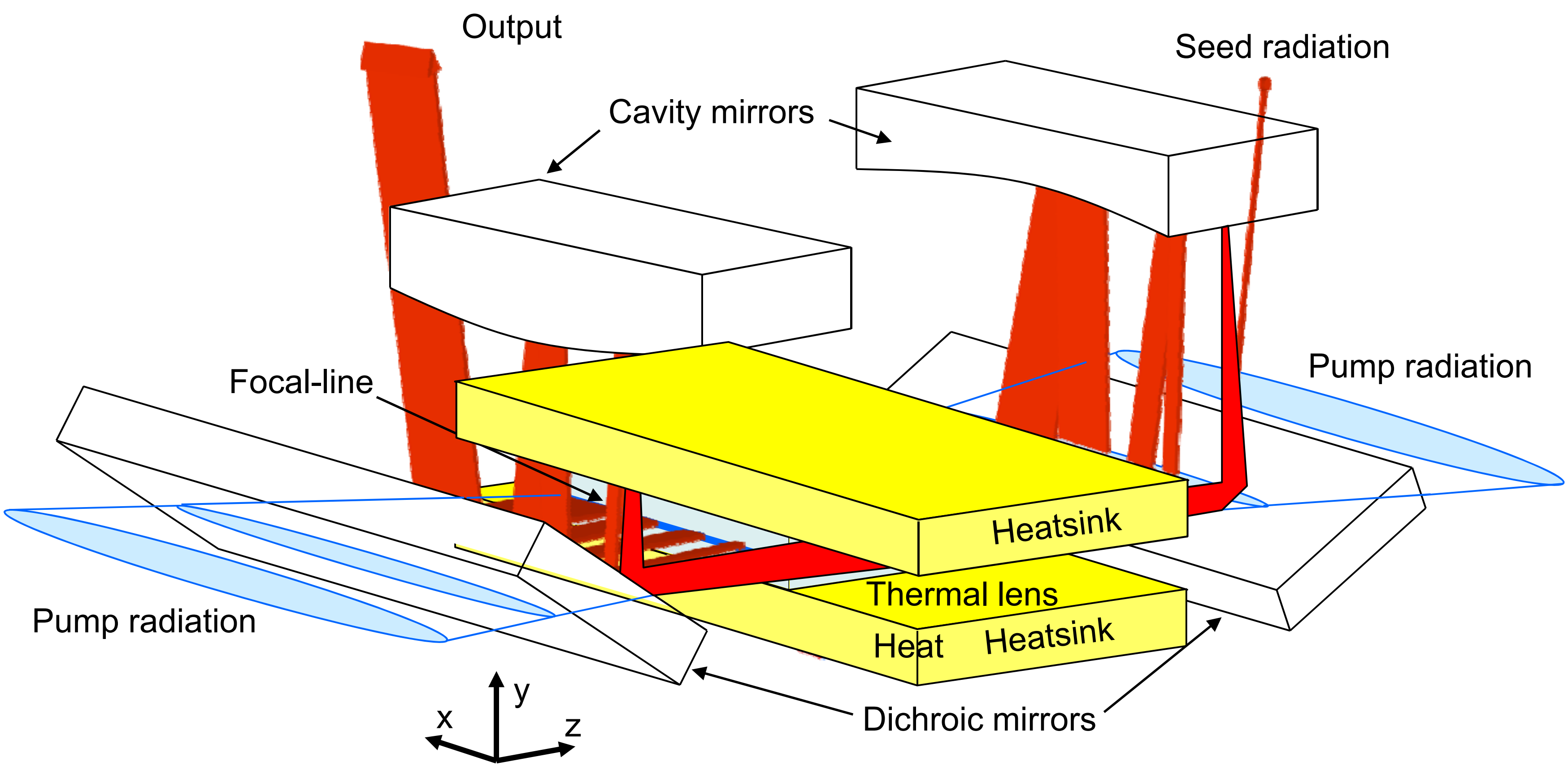
- Large amplification lengths due to adapted folding technique
- High amplification at low beam quality distortion
- Simple adaption of beam size to saturation properties of medium
- optional polarization coupling of two separate lines in final amplifier

Diode Seeder for flexible Pulse Generation of 0,5 – 1.5 ns

- Rugged and stable concept
- Control of emission wavelength by grating and temperature
- Pulse shape variable
- External Trigger available
- Computer controlled pulse parameters
- Pulse energy < 1 nJ requires regenerative Amplification



Slab-laser amplifier – basic design



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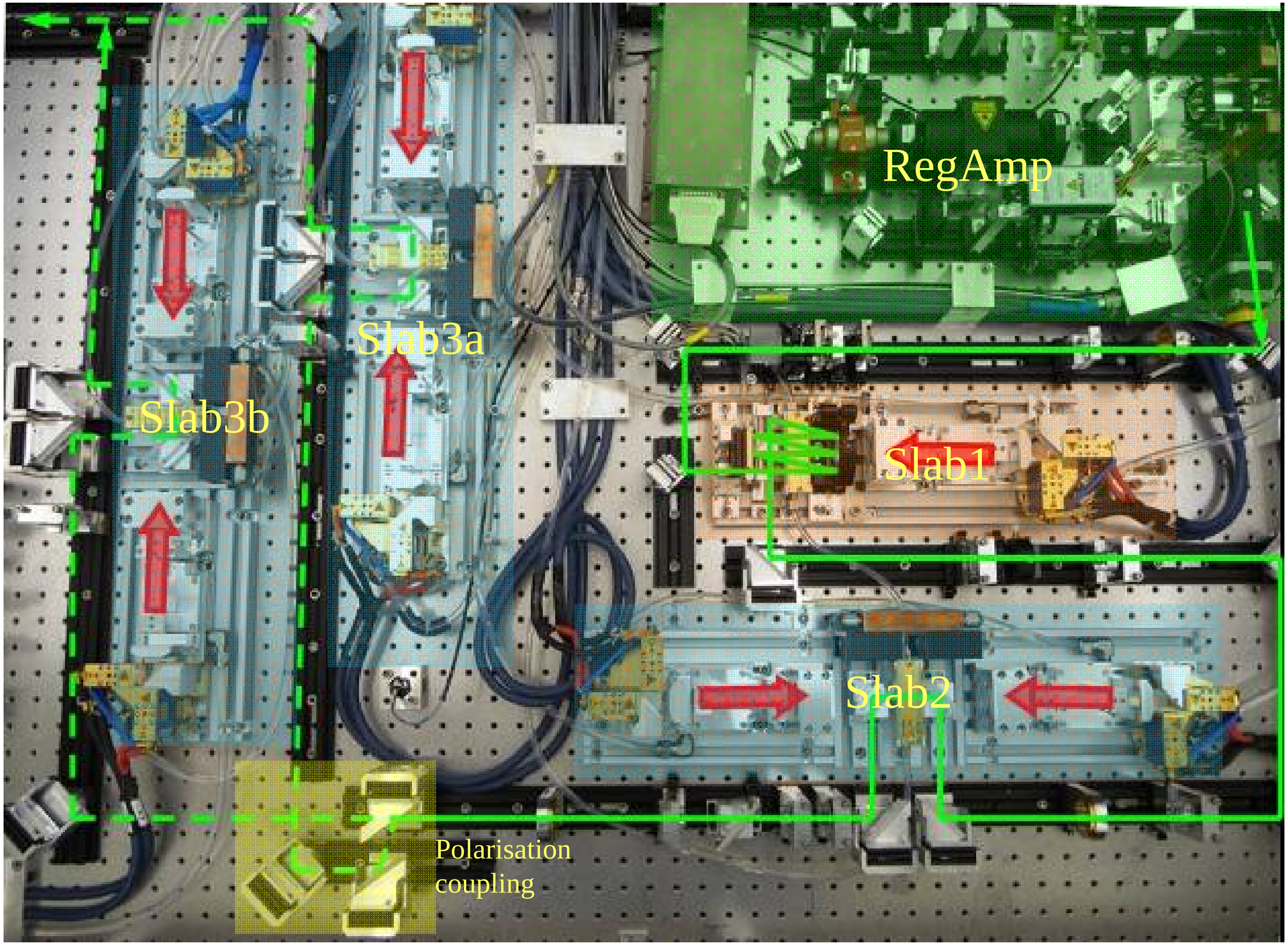
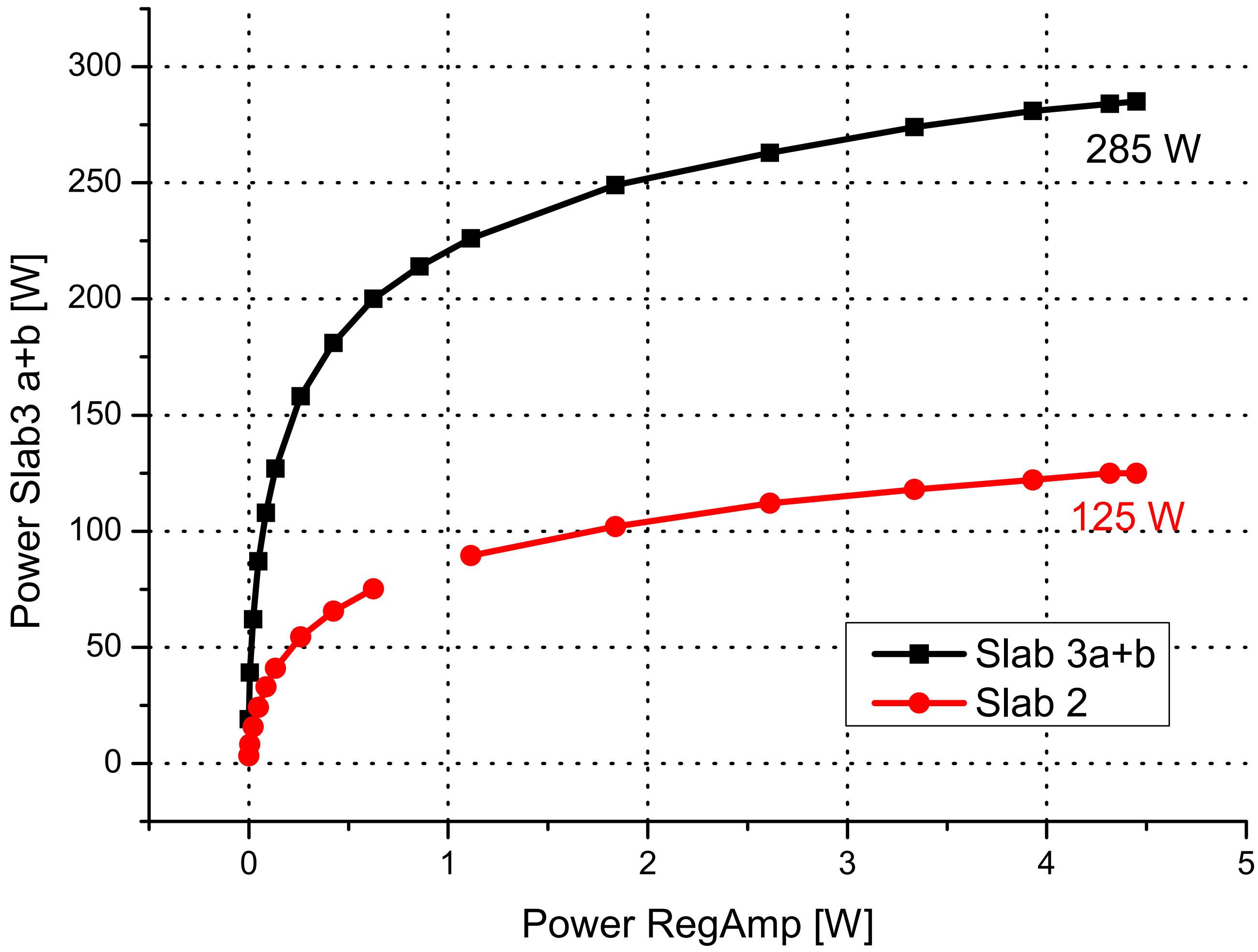
Laser prototype setup, 150 mJ version



IR Laser Output of Polarization Combined Power Amplifiers



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150 mJ – Laser: final results

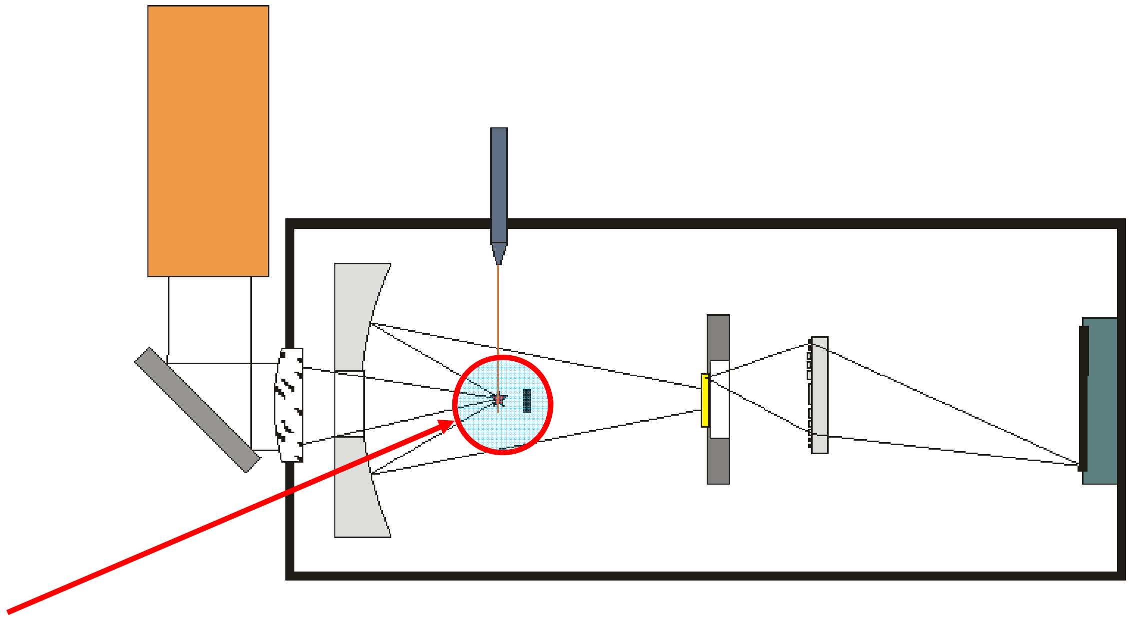
Design Goals

pulse duration	0,5 – 2 ns
wave length	1064 nm
pulse energy	150 mJ
power	300 W
rep. rate	2 kHz
contrast ratio	> 500:1
M^2	< 2

Demonstrated parameters

pulse duration	~ 0,4 ns	✓
wave length	1064 nm	✓
pulse energy	140 mJ	(✓)
power	280 W	(✓)
rep. rate	2 kHz	✓
contrast ratio	> 500:1	✓
M^2	1.4 / 3.4	(✓)

XUV-results



- one laser @ KTH/Stockholm under preparation for the use in the x-ray microscope (actually: laser characterization and qualification)
- one laser @ MBI/Berlin under initial operation for XUV-production, with the actual data (work in progress):
  - XUV-power more than $5 \cdot 10^{14}$ ph/s/sr @ 90W laser power (1,3kHz repetition rate)
  - plasma source size not yet measured, estimated to 20 - 50µm diameter
  - stable operation, optical isolators mandatory
  - thanks to: Herbert Legall, Gernot Blobel und Holger Stiel/MBI Berlin

Summary / Outlook

- Average power of up to **280W @ 2kHz** prf out of two coupled beam lines demonstrated
- Peak power of more than **200MW** is achieved without beam distortion by nonlinear effects or optical damage
- Contrast ratio better than **500:1**
- Beam quality in the range of **M^2 < 1.4 … 3.4** allows efficient plasma generation
- Pulse length can be set from **0.4 ns to 1.5 ns**
- Reduction of pulse energy from 140 mJ to about 50 – 100 mJ considerably **simplifies the setup**

- **Further power scaling by increasing PRF should be possible !**

Acknowlegments

Thank you to the development team @ Fraunhofer-ILT:

Marco Höfer, Dominik Esser, Henrik Sipma, Raphael Kasemann, Hans-Dieter Hoffmann

Part of this work was sponsored by:

Bundesministerium für Bildung und Forschung

In Cooperation with:

MAX-BORN-INSTITUT

KTH ROYAL INSTITUTE OF TECHNOLOGY

BRUKER