TEC
TRILATERAL
EUREGIO CLUSTER

JÜLICH
FORSCHUNGSZENTRUM

Application of laser techniques for first wall characterisation

**A. Huber, B. Schweer, V. Philipps, N. Gierse,
M. Zlobinski, S. Brezinsek, W. Biel, V. Kotov,
R. Leyte-Gonzales, Ph. Mertens, U. Samm**

General background

Post mortem analysis of wall tiles has been shown to be the most important tool to diagnose material erosion, deposition , fuel retention and wall situation in general, but

- **Needs physical removal of tiles**
- **Integrates over long term operation**

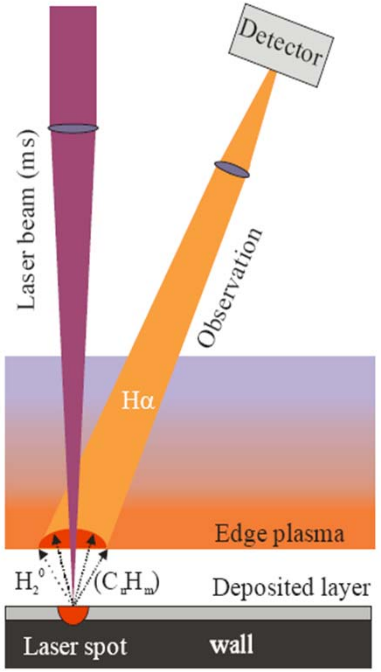
Can hardly be done in ITER and future reactors

new program has been initiated in FZJ

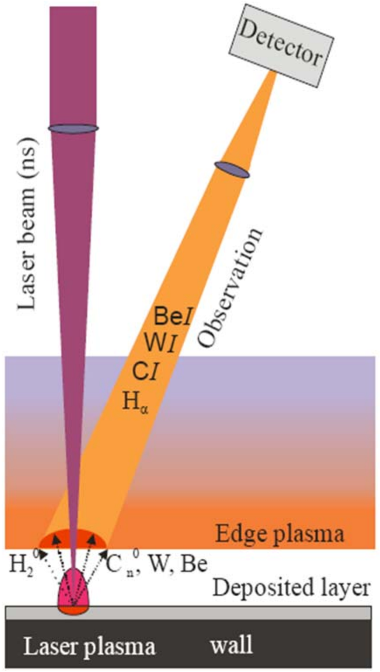
Develop methods to characterise in situ material deposition and fuel retention in fusion devices based on laser techniques

Laser-based diagnostics

Three laser methods have been selected for detailed analysis in Lab- experiments (if needed) and TEXTOR application , with the goal to develop a prototype ITER- like system

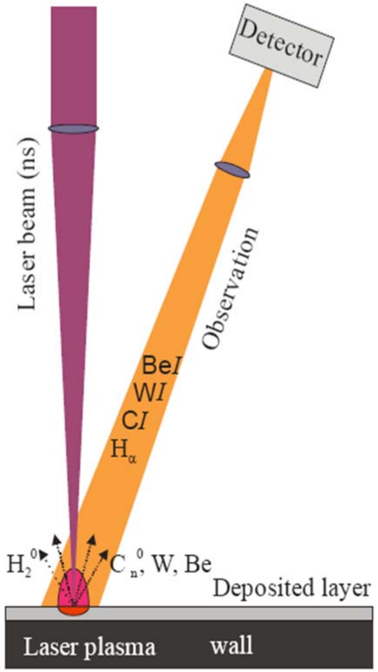


LIDS: Fuel desorption by smooth spot laser desorption (no ablation) with spectroscopic H detection with tokamak plasma
(ms laser)



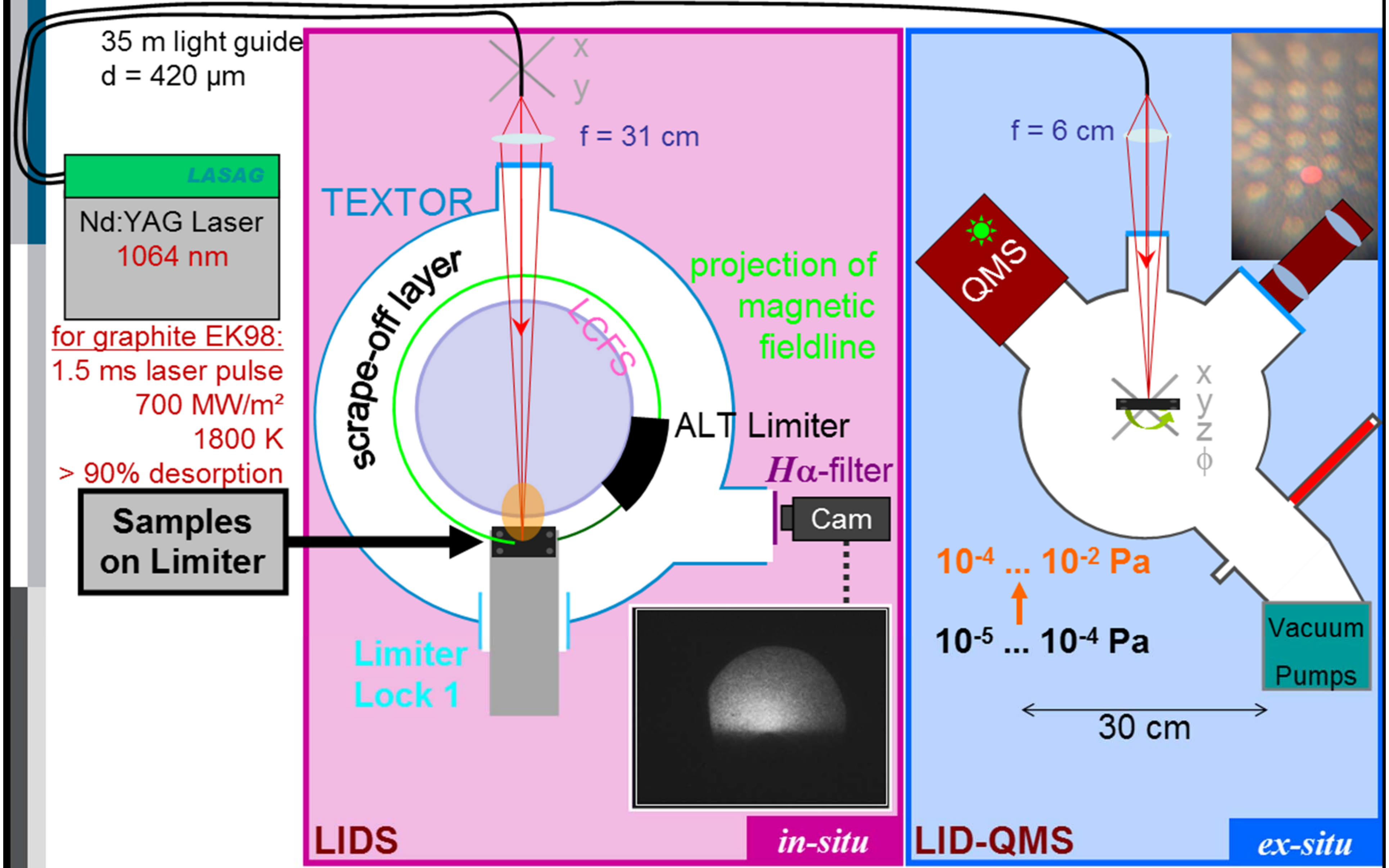
LIAS: Material ablation by intense spot laser heating with spectroscopic detection with tokamak plasma

(ns and ps laser)



LIBS: Material ablation by intense spot laser heating with spectroscopic detection in laser plasma
(ns and ps laser)
(no tokamak plasma)

Experimental Setup for LID in Jülich

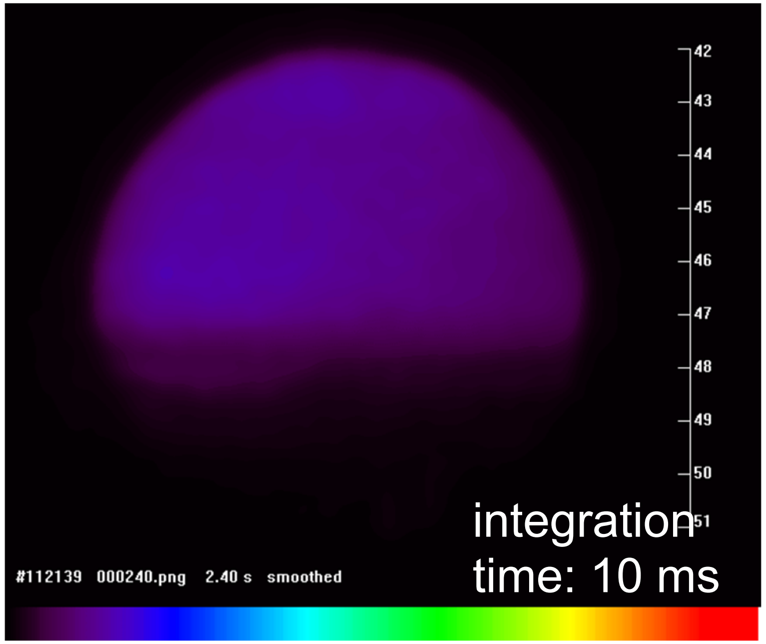


for graphite EK98:
1.5 ms laser pulse
700 MW/m²
1800 K
> 90% desorption

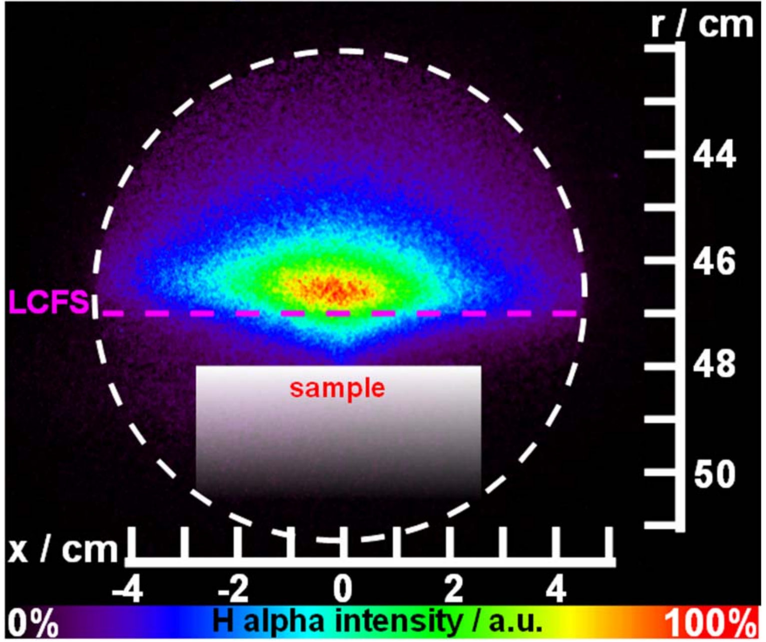
Samples on Limiter

LIDS on TEXTOR

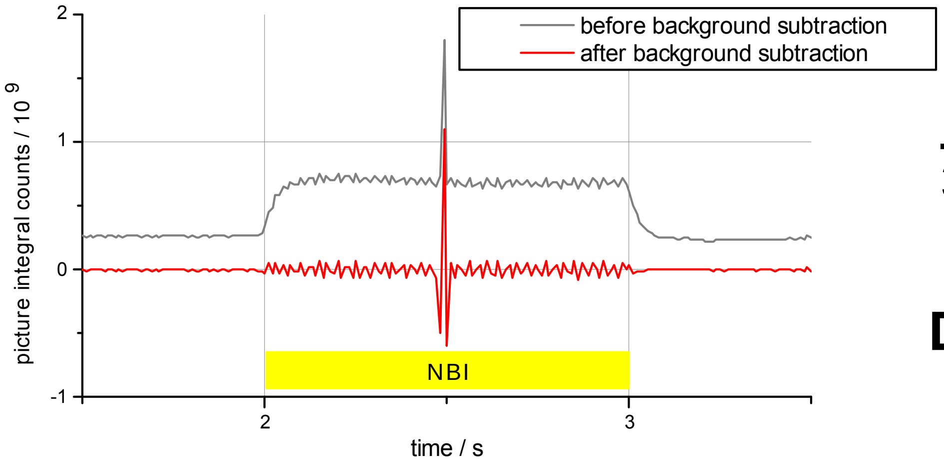
H-alpha light: background



During Laser pulse



Retention: 3 10^{22} D/m^2



Integration time: 10 ms

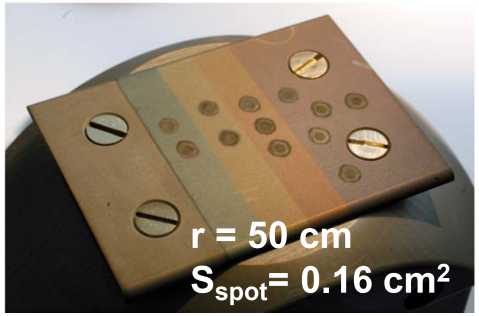
Laser parameters:

3 ms , 7.9 J , spot size: 5.3 mm^2

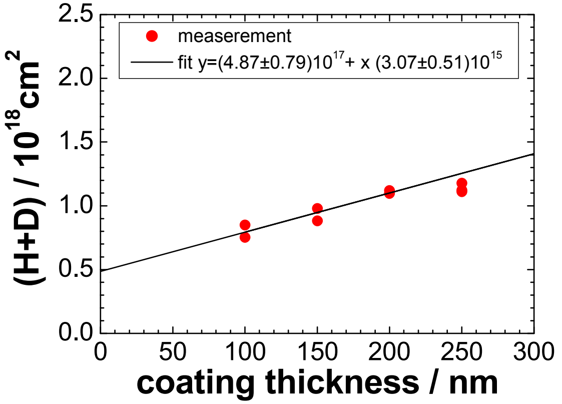
Detection limit:

- **NBI phase: $3 \cdot 10^{21}$ H/m^2**
- **ohmic phase: $4 \cdot 10^{20}$ H/m^2**

Laser-induced desorption in TEXTOR

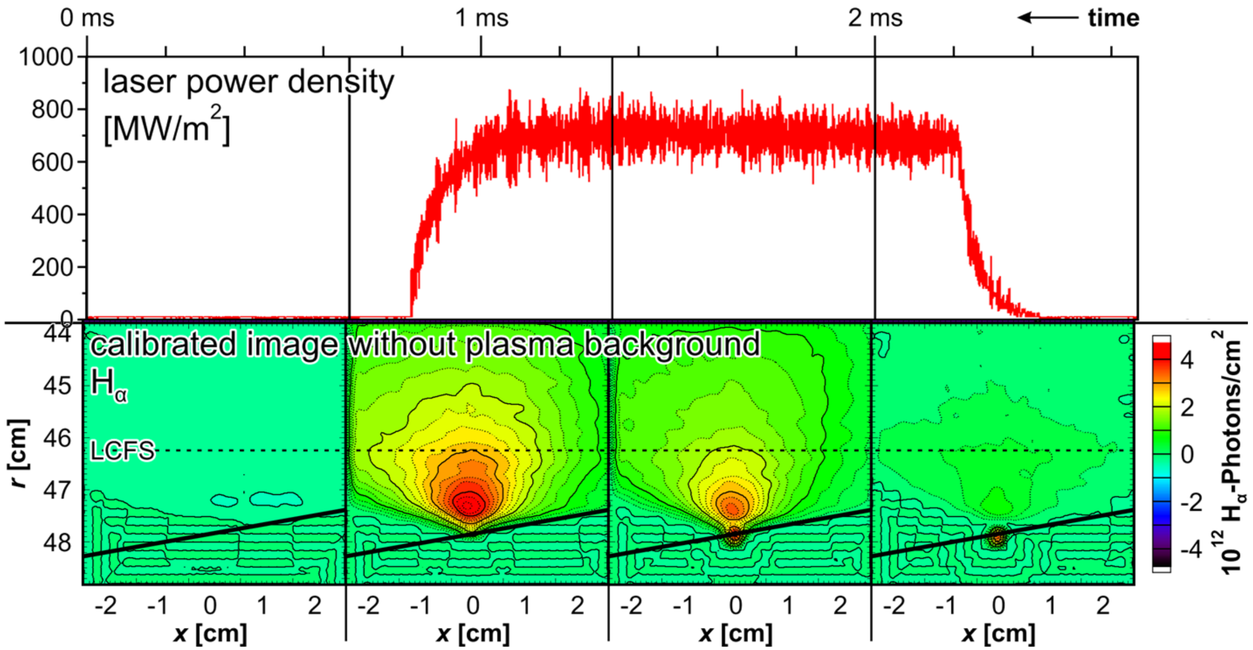


Graphite EK98 target with a-C:D coatings for calibration



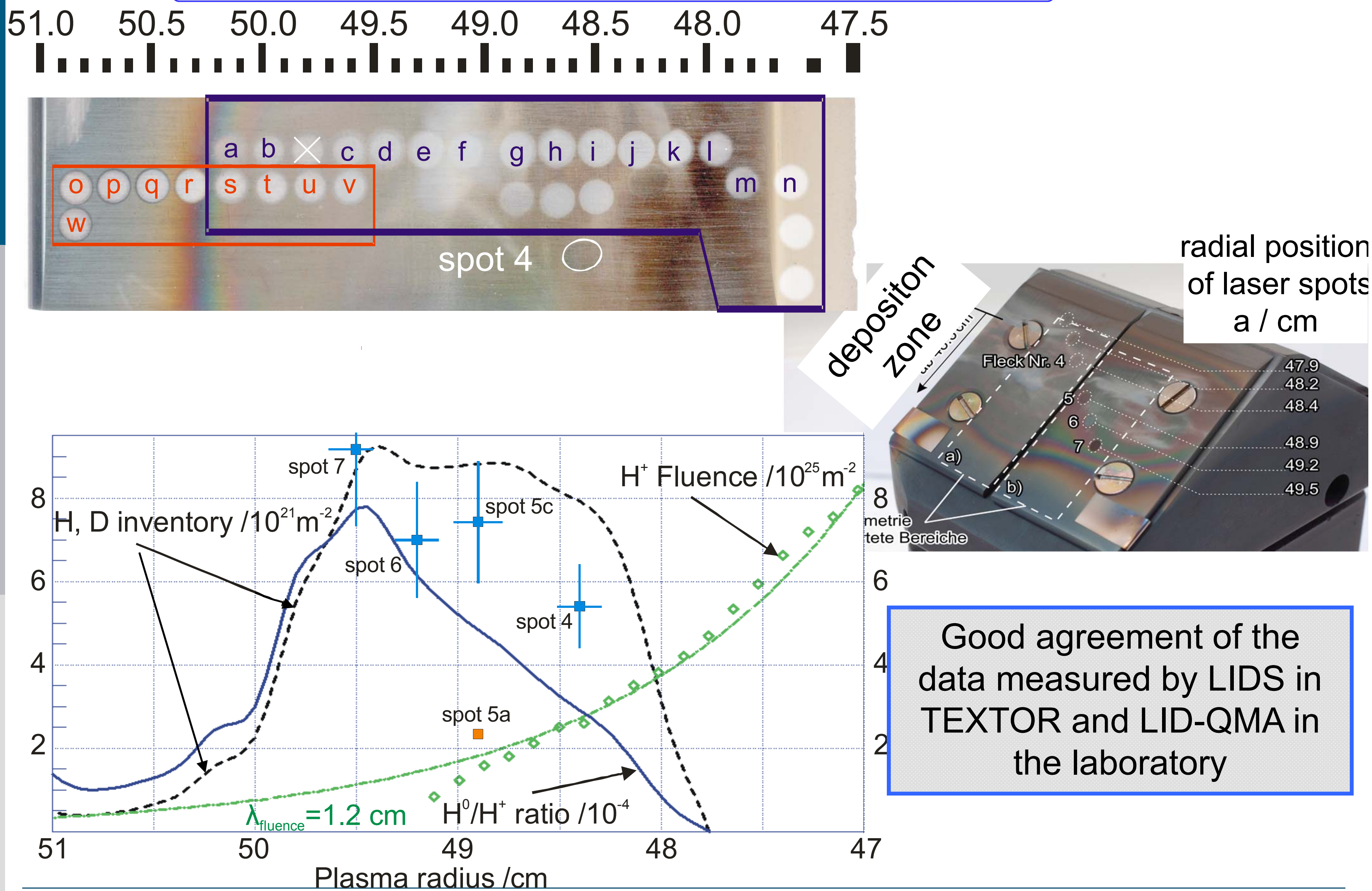
Graphite EK98 target with a-C:D coatings for calibration

T_{surf} up to 1800 K is achieved by absorption of laser radiation with P_{laser}≈70 kW/cm² for about 1.5 ms. More than 95 % of hydrogen in thin (<1µm) a-C:D layers is released in a single laser pulse.



LIDS has been qualified in TEXTOR to measure fuel retention in C materials, *in situ* and shot by shot.

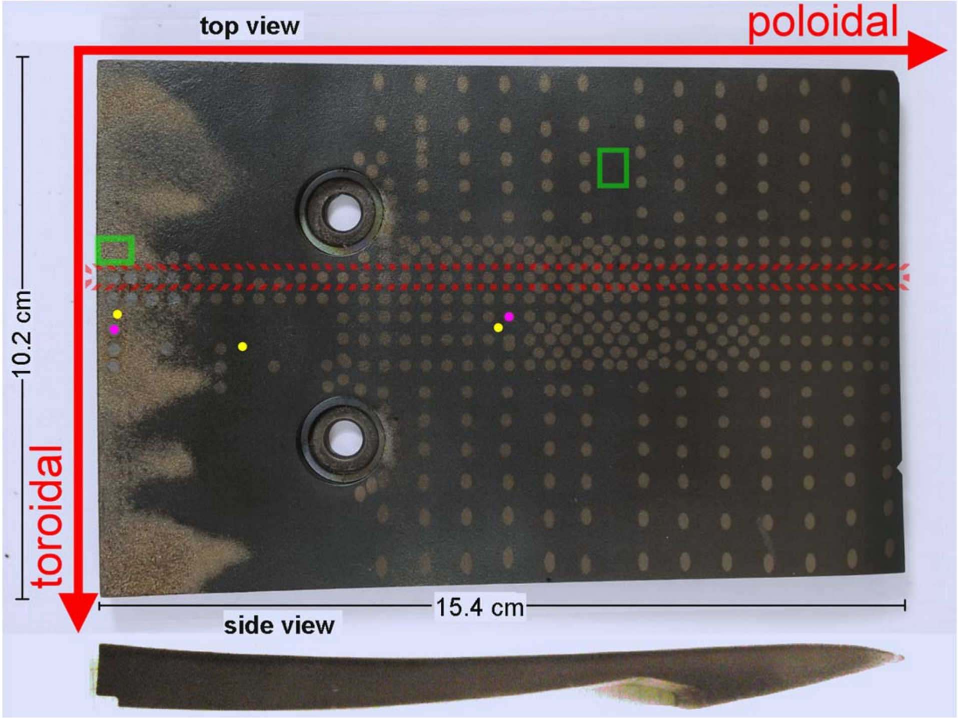
LIDS: Result on TEXTOR vs Lab

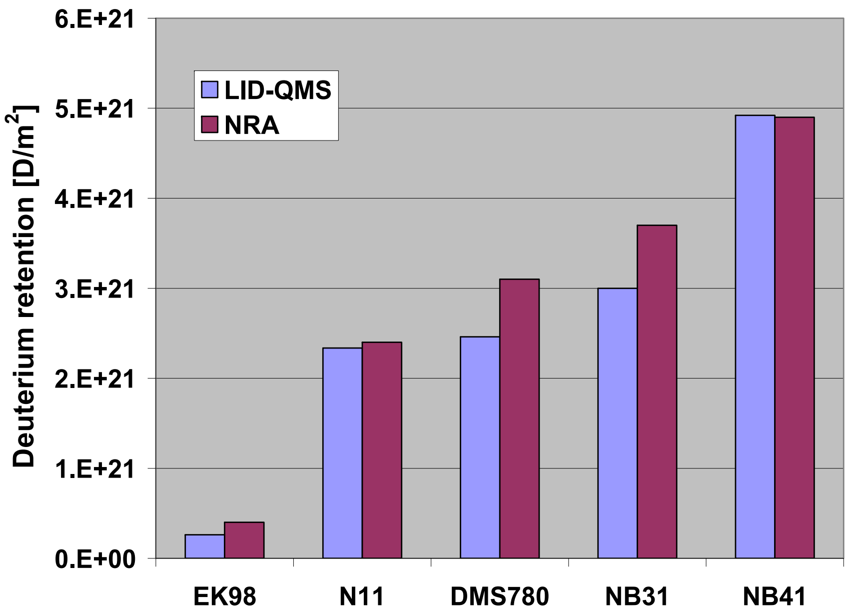


radial position of laser spots a / cm

Good agreement of the data measured by LIDS in TEXTOR and LID-QMA in the laboratory

Laser spot heating in Lab experiments (LID-QMS)





Laser mapping of H inventory (LID- QMS) of TEXTOR limiter tile

Good agreement with TDS and NRA

Comparison of LID with NRA on graphites exposed to TEXTOR (150sec)

Status of LIDS at FZJ

Work performed:

Investigation of a-C:H layer

Hard layers (≤1000 nm)

1.5 ms (<4ms)

70 kW/cm^2

T≤1800 K

With increasing temperature release of:

Hydrocarbon <10%

H_2 molecules majority

H-atoms <5%

Sensitivity 10^{17}/cm^2

Spot size 0.1 cm^2

Ongoing work: Investigation of tungsten

Measurements of D content in W layers

- target temperature dependence
- flux density or fluence dependence
- plasma temperature dependence (deposition depth)

Laser effects

Reflection coefficient (surf. temperature)

H/D release efficiency / temperature dependence

Laser-induced ablation (LIA)

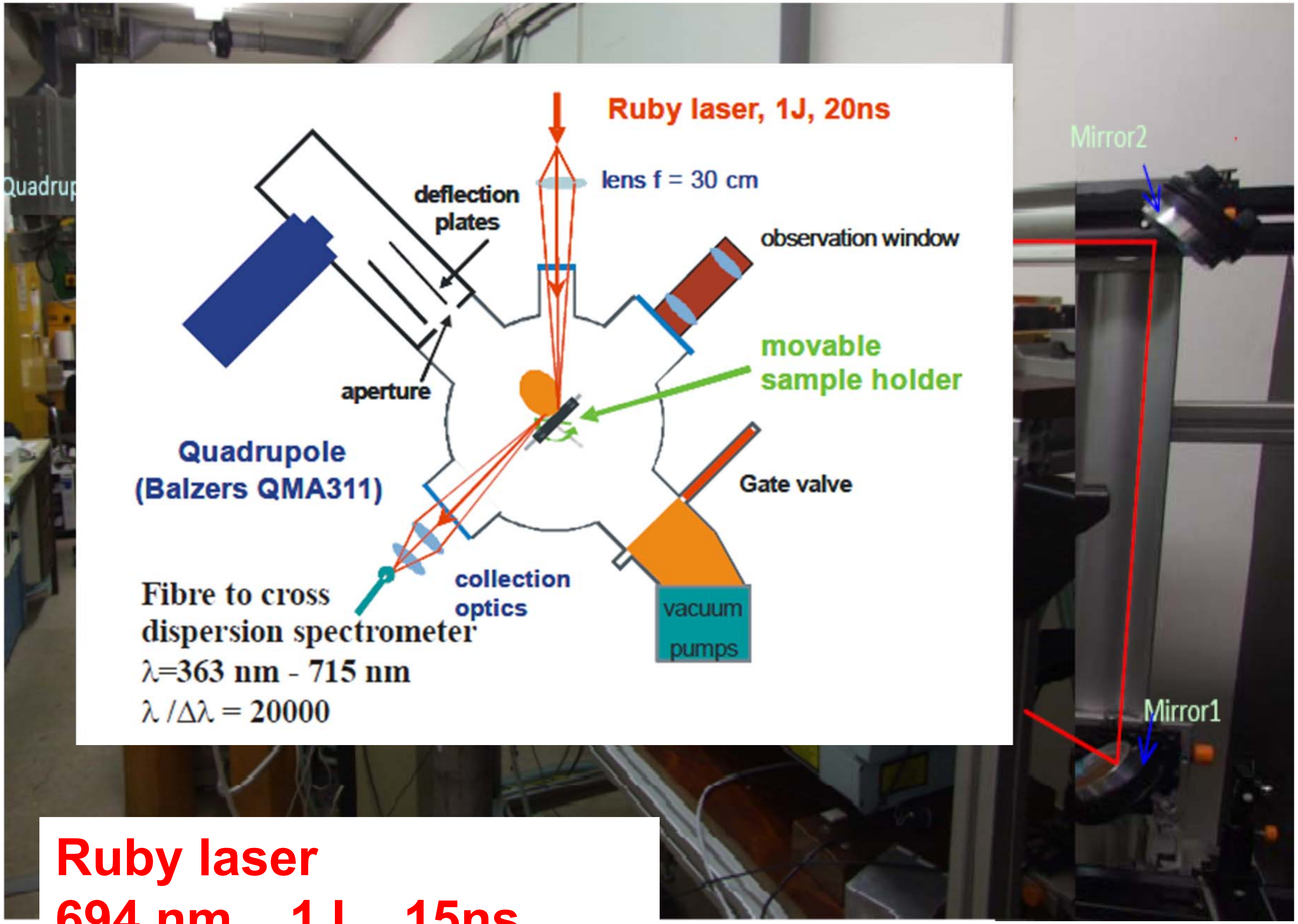
Q-switch Ruby laser:
TEXTOR: $E \leq 15$ J, $t_{pulse} \leq 10$ ns, 1,5 $\leq$GW, $\lambda = 694$ nm, 1 pulse /s
Laboratory: $E \leq 1$ J, 1 pulse /s

Method:

1. Absorption of power
   Breaking of C bonds, few eV
2. Production of dense plasma
   but fast neutralization of ions
   Majority are neutrals
3. Production of jet beam ±10° with particle energies of a few eV
4. Determination of the composition of the residual gas by quadrupole mass spectrometer (QMS)

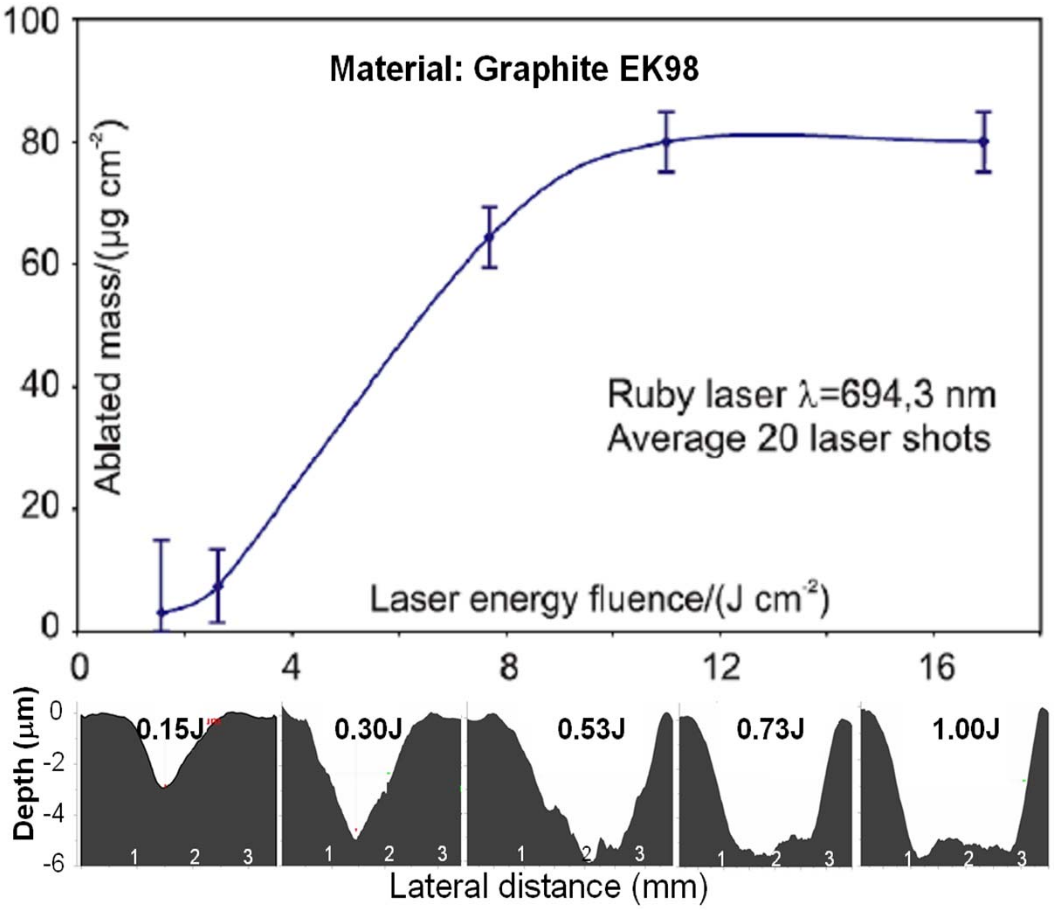
TEXTOR: ablation of a-C:H layers on graphite and tungsten limiter
Laboratory work:
Energy distribution (ToF), species distribution, ion fraction of the beam, formation of cluster, reproducibility (particles/pulse)
Wavelength dependence for ablation (Nd:YAG, Ruby, Excimer)

Lab experiments for LIAS and LIBS



Ruby laser
694 nm, 1J , 15ns

LIAS: Laser induced Ablation Spectroscopy

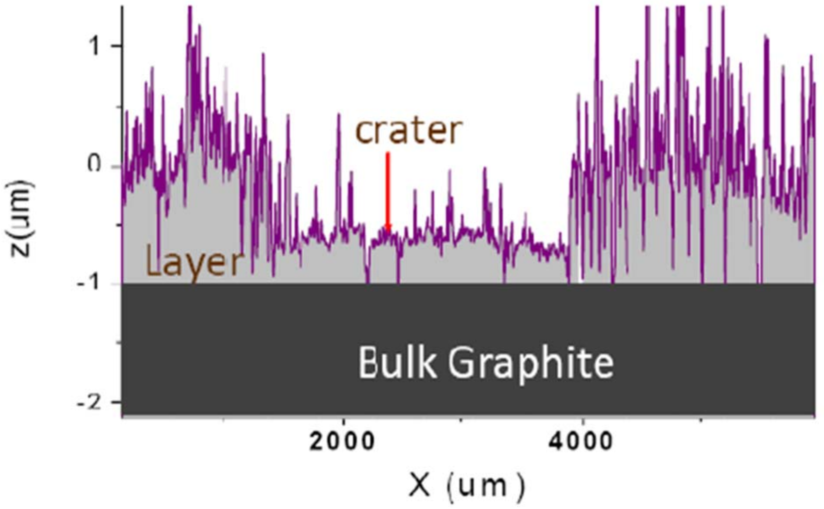


The ablation rates: were in the range of ~0.3÷0.6µm/shot in the energy density range of ~2.6÷7J/cm2 and saturates at about ~0.6µm/shot for higher energies.

the ablated carbon mass normalized to an area of 1cm^2 saturates at about 10J/cm^2.

Laser ablation of C layers ongoing

reduced threshold for ablation

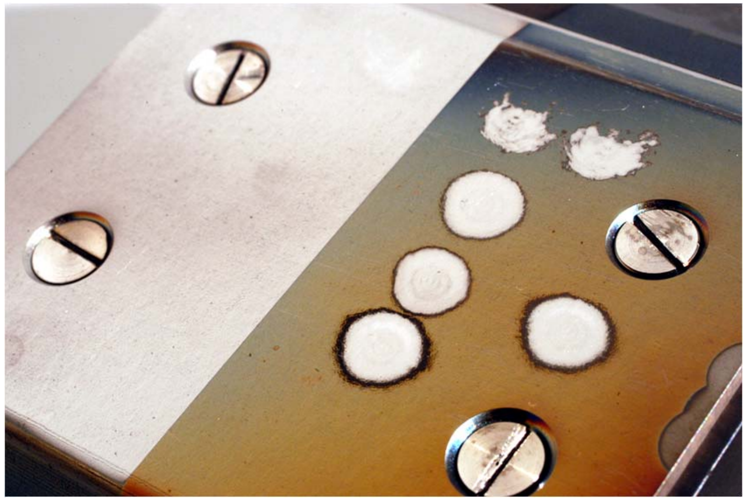


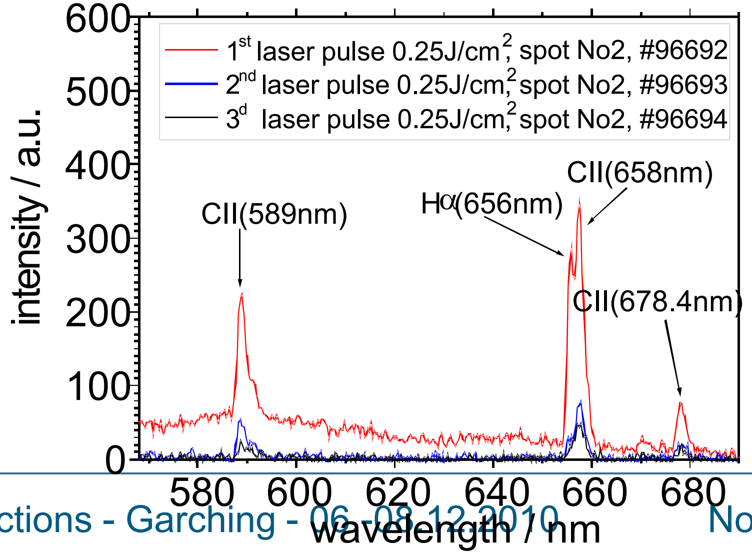
Crater profile of a a-C:D layer in one single laser shot at 1 J/cm2

Below threshold for bulk C ablation

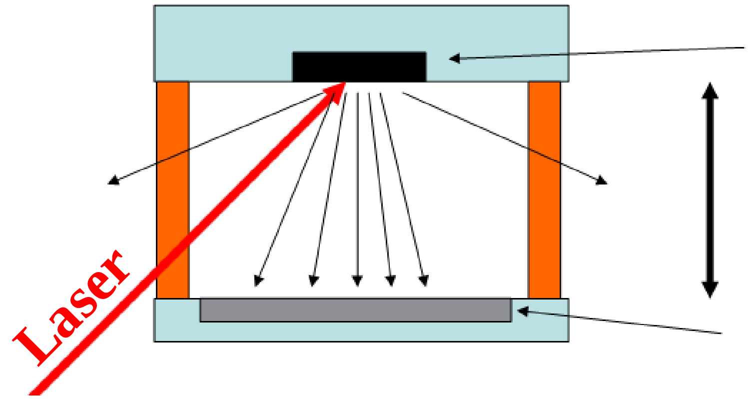
low ablation threshold (≈0.25J/cm2) for a C layer of 140 nm thickness on tungsten subtract

Ablation of a-C:D on W in TEXTOR at 0.25 J/cm^2 (!!)





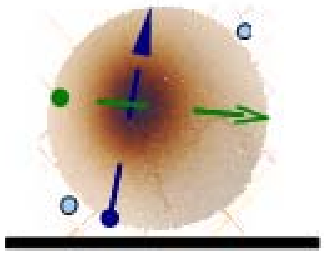
Angle distribution, mass loss and gain



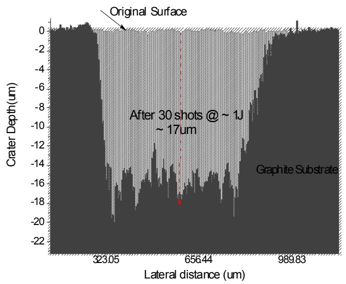
Carbon sample (EK98)

Distance: 40 mm

Aluminum Plate

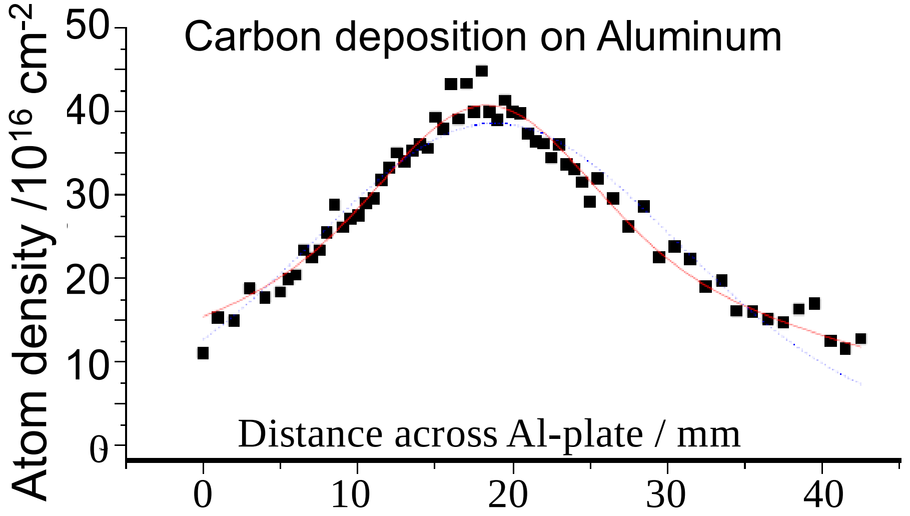


Mass gain 65µg



Mass loss 80 µg

EPMA results (angle distribution)



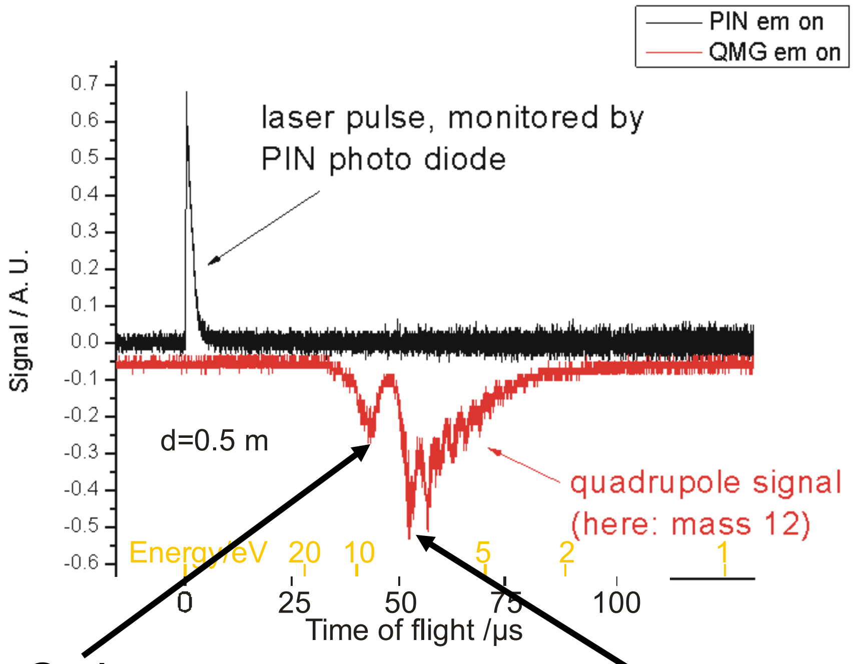
Angle distribution:

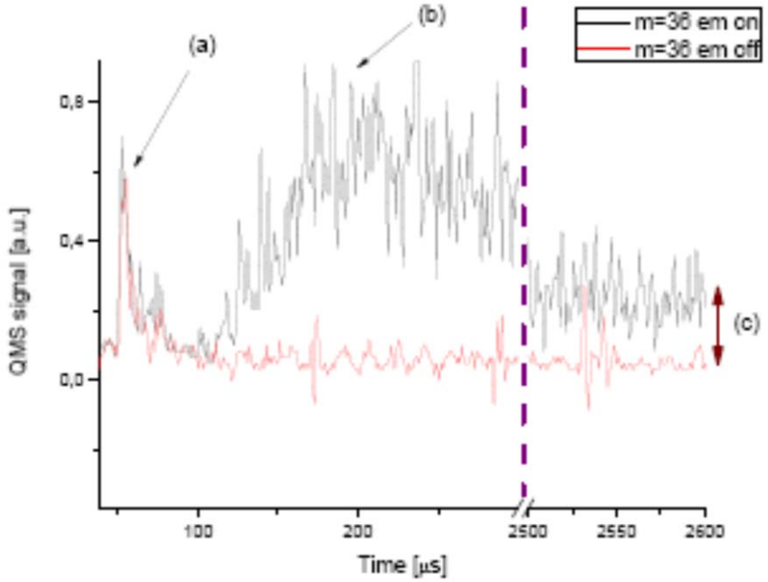
$$I(\varphi) = A(\cos\varphi)^n + \cos\varphi$$

n>= 24

collected mass : 80%

Time of flight measurements





C^+ ions

C atoms

- First peak (energy 10 eV) attributed to C_1^+
- Second peak is due to neutral carbon atoms (only with emission on)
- C_1 neutral energy ≈ 6 eV, (depends somewhat on the energy fluence).
- C_1 signal intensity about a factor of 1000 larger than the C_2 and C_3 values

Laser-induced breakdown spectroscopy (LIBS)

Release process identical to LIAS

But spectroscopic observation of laser-induced plasma (between discharges)

Established method in material analysis, but in gaseous atmospheres

Application under UHV conditions

Small detection volumes but no other background light

Influence of permanent magnetic field?

FZJ activities:

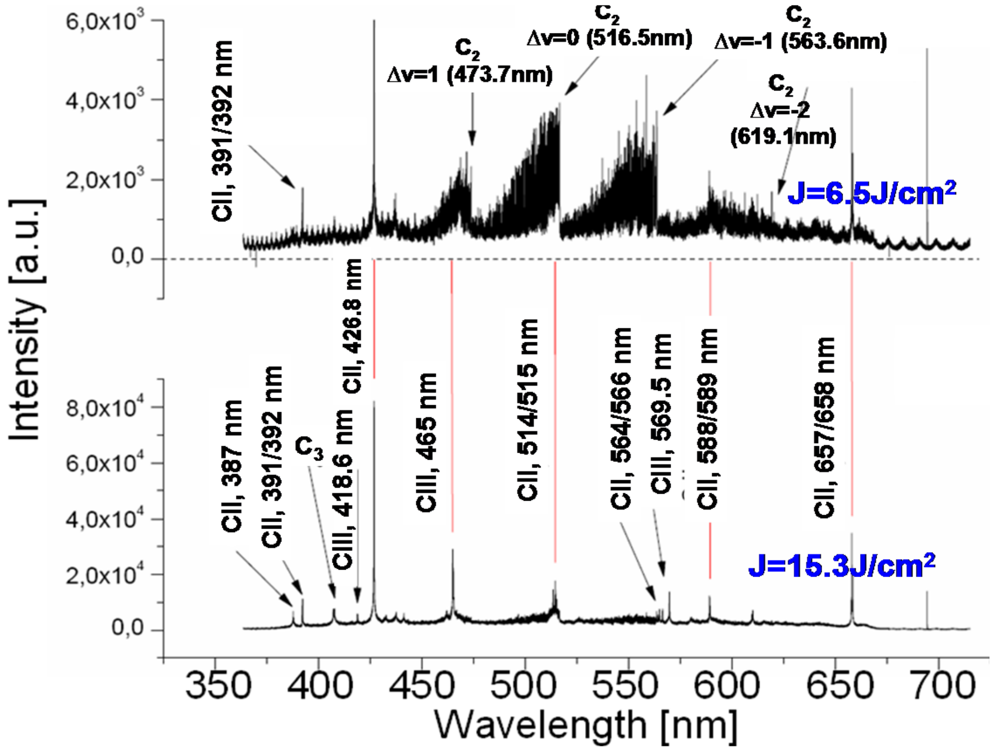
will be included in LIA work

At laboratory: comparison spectroscopy and QMS results

development of spectroscopic lines conversion factors

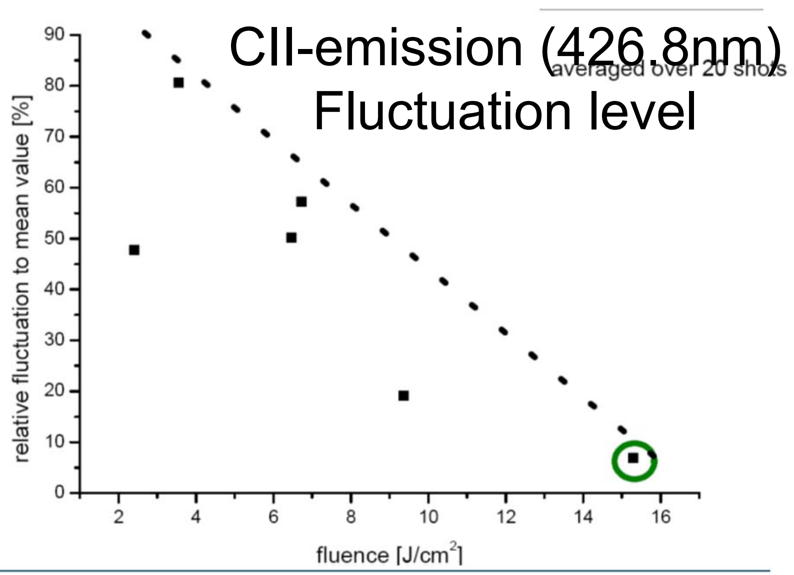
At TEXTOR: influence of toroidal magnetic field

Laser-induced breakdown spectroscopy (LIBS)



High resolution spectral line emission

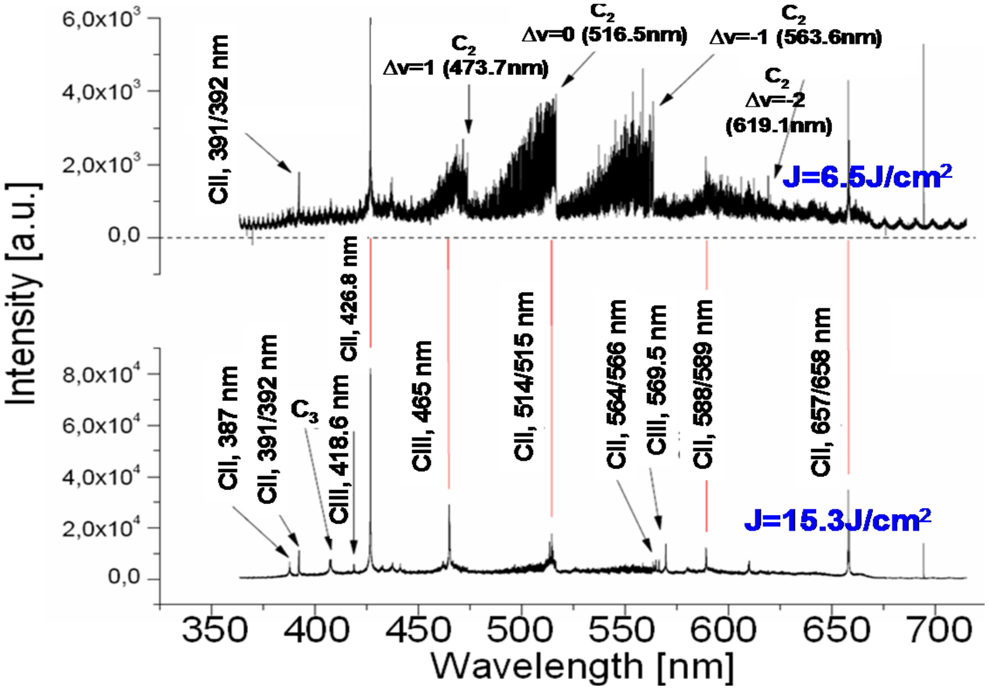
More ions appear at higher energies

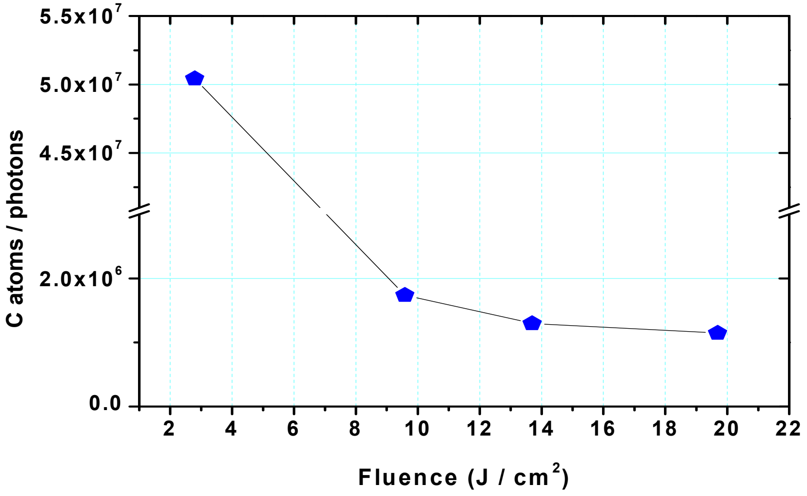


CII-emission (426.8nm)
Fluctuation level

The operation at a laser fluence below 8J/cm² is not meaningful for analysis of the ablated layer in a single laser pulse and is not recommended for ITER operation.

Laser-induced breakdown spectroscopy (LIBS)



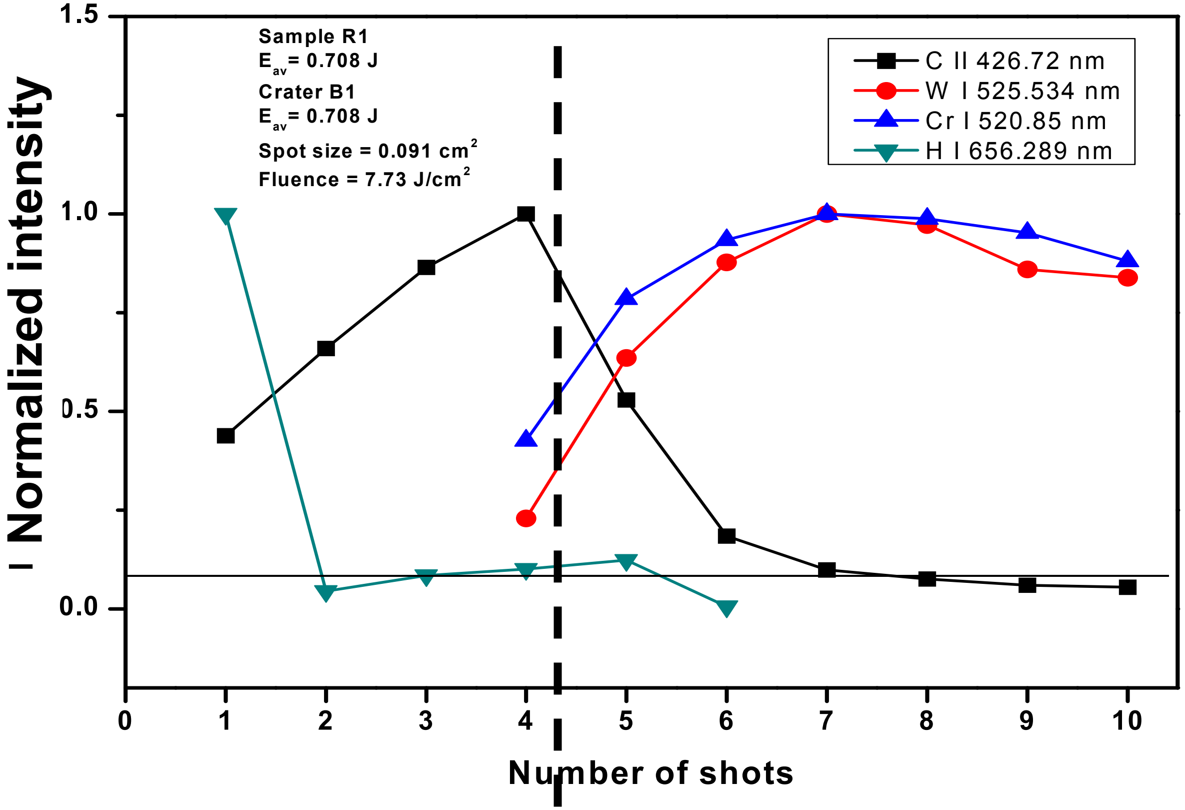


High resolution spectral line emission

More ions appear at higher energies

For energy fluences above 10J/cm² on fine grain graphite (EK98), a ratio of the ablated atoms to the number of CII line photons, $C_f = N^C/I(\text{photons}) \approx 10^6$ was found.

(LIBS)



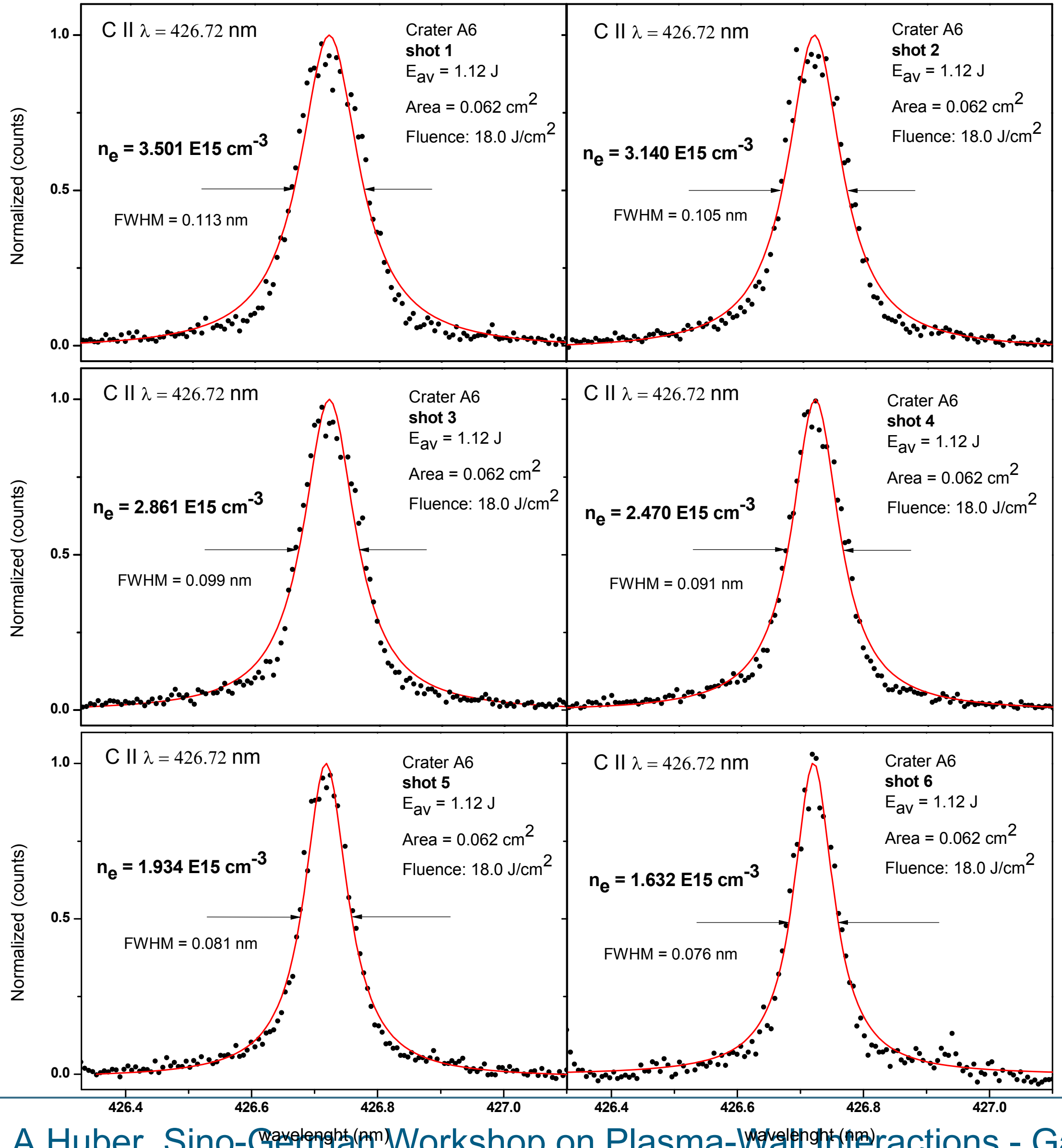
interlayer

Hydrogen is reduced after first laser shot

Carbon stays until layer is removed

LIBS spectra from a 3.2 µm thick a-C:H layer on W substrate with a Cr interlayer

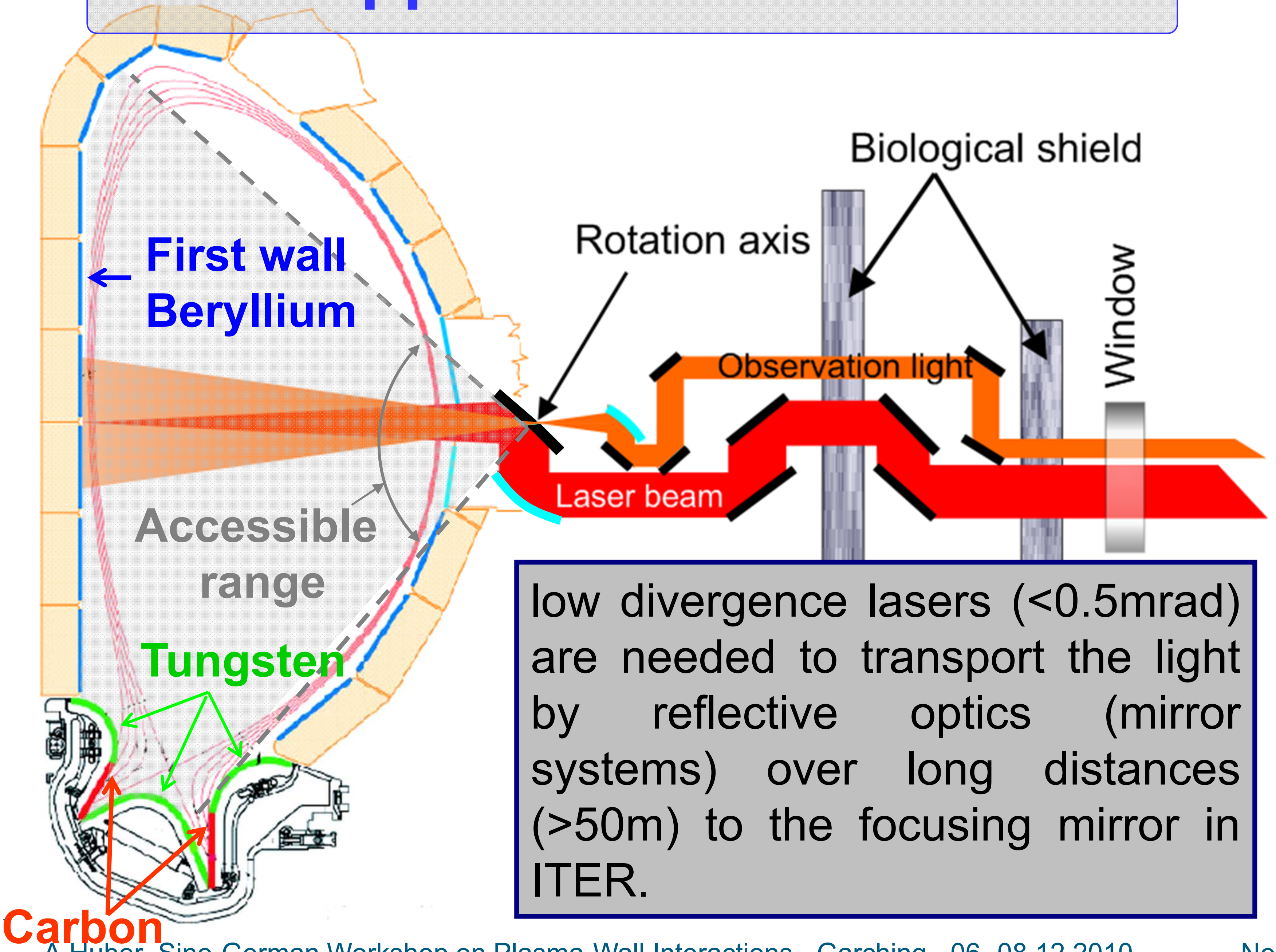
Laser-induced breakdown spectroscopy (LIBS)



Laser-induced plasma parameters strongly depend on the composition of the ablated layers

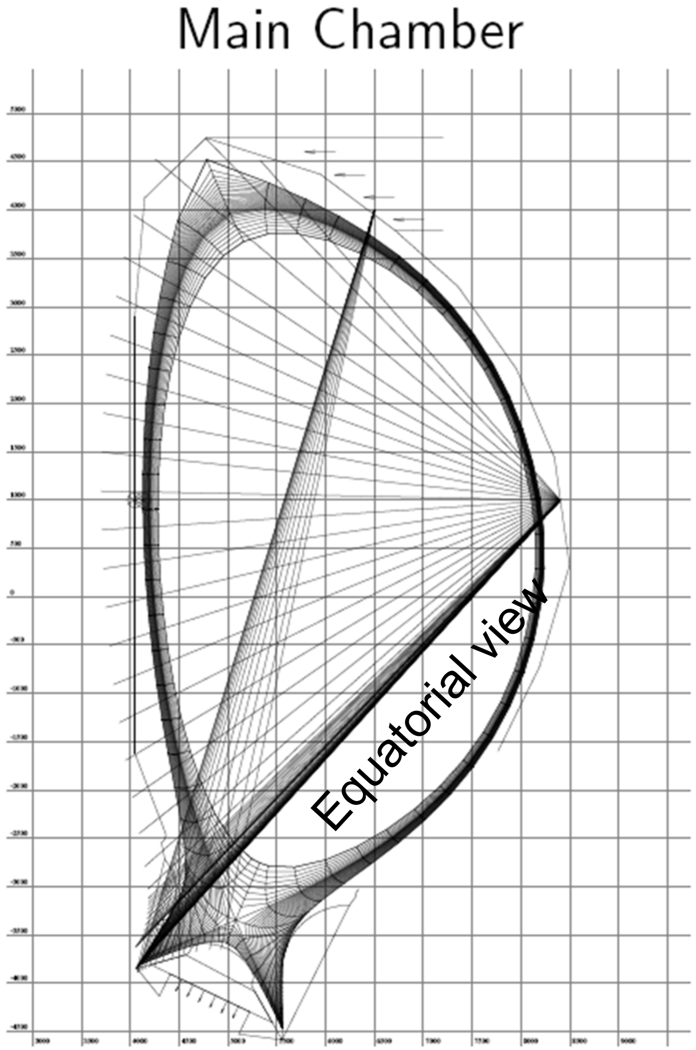
Electron density variation
for different laser shot numbers

Application to ITER



low divergence lasers (<0.5mrad) are needed to transport the light by reflective optics (mirror systems) over long distances (>50m) to the focusing mirror in ITER.

B2-Eirene modelling for LIDS in ITER: LIDS signal versus background plasma



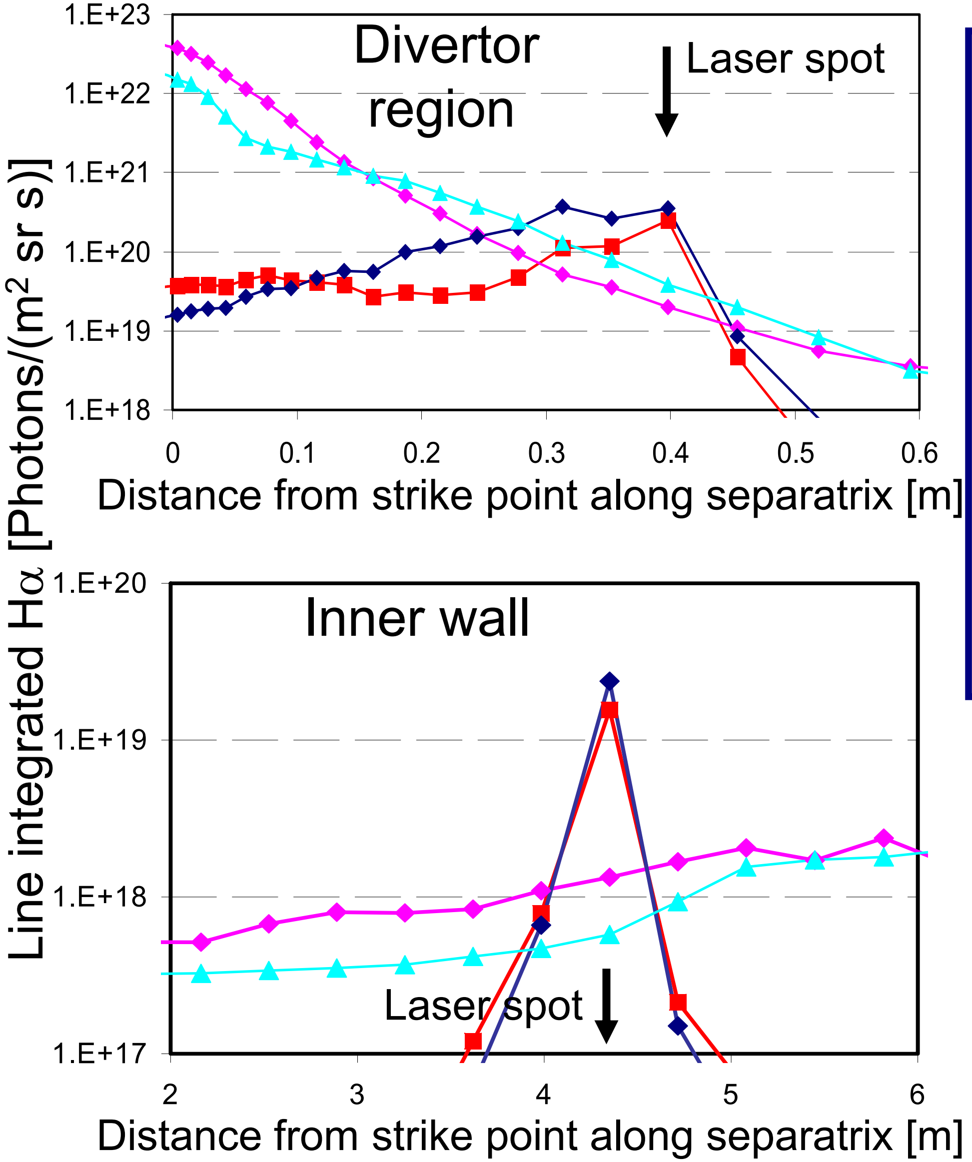
Assumptions:

Laser spot size:	$A=1cm^2$
H density:	$n_H=3\cdot10^{15}/cm^2nm$
Layer thickness:	$100nm\ (3x10^{21}/cm^2)$
Pulse duration:	$t=1ms$
Maxwellian source:	$T=0.2$ eV
H- Flux	$\Gamma_{spot}=3\cdot10^{20}/s$

- Reference ITER scenario, P_{SOL} =100 MW, $f_{rad}\approx 2/3$, (partially) detached divertor
- Kotov V. et al. Contrib. Plasma Phys, **46**, 635 (2006)
- Ly-lines opacity is taken into account
- High Density Case: p_{PFR}=11 Pa, q_{peak}= 5 MW/m^2
- Low Density Case: p_{PFR}=6 Pa, q_{peak}= 8 MW/m^2

Performed for ITER low and high density reference scenarios

LIDS signal versus background plasma in ITER



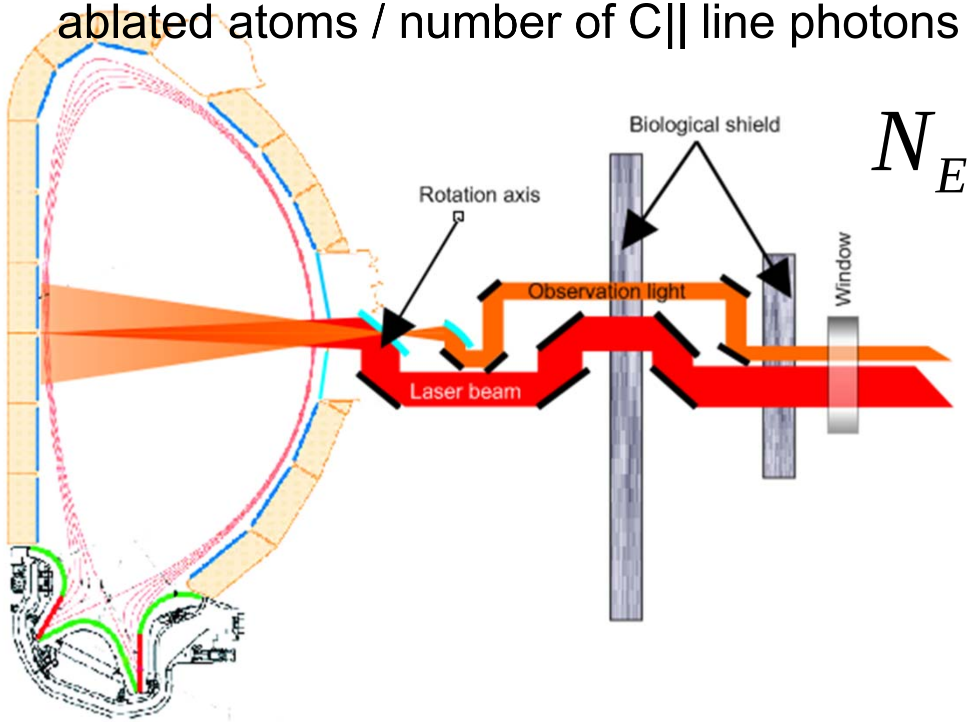
S/N ratio above 10 at the divertor target could be achieved only for distances more than 0.4m away from the strike point.

To be able to determine the H isotopes retention in the vicinity of the strike point the thickness of the co-deposited layer should be more than 100μm.

S/N ratio above 10 for a laser spot of 1cm^2 at the inner wall close to the equatorial plane

Sensitivity of LIBS method

For energies > 10 J/cm^2 on carbon (EK98) , a ratio of 10^6 was found of ablated atoms / number of C|| line photons

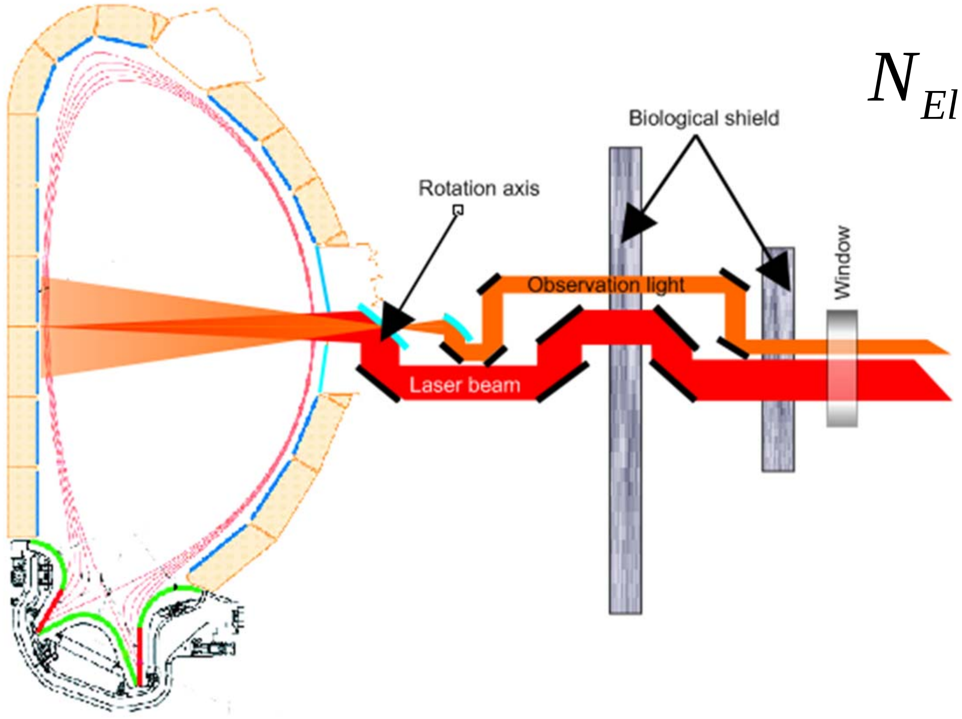


$$N_{El} = \left[N^C / C_f\right] \times T \frac{\Delta\Omega}{4\pi} \eta$$

$\Delta\Omega = 2\times10^{-6}$ sr is the solid angle
T=0.1 is the transmission factor of the optical system
η=10% is the quantum yield of the detector.

To obtain a good photoelectron statistic $1/\sqrt{N_{el}} \leq 3\%$ to resolve the LIBS signal, about 10^{18}C atoms must be ablated. This corresponds to the content of carbon atoms in a 100 nm layer.

Sensitivity of LIAS method



$$N_{El} = \left[N^{C} / (S/XB)\right] \times T \tfrac{\Delta\Omega}{4\pi} \eta$$

$\Delta\Omega = 2 \times 10^{-6}$ sr is the solid angle
T=0.1 is the transmission factor of the optical system
η=10% is the quantum yield of the detector.

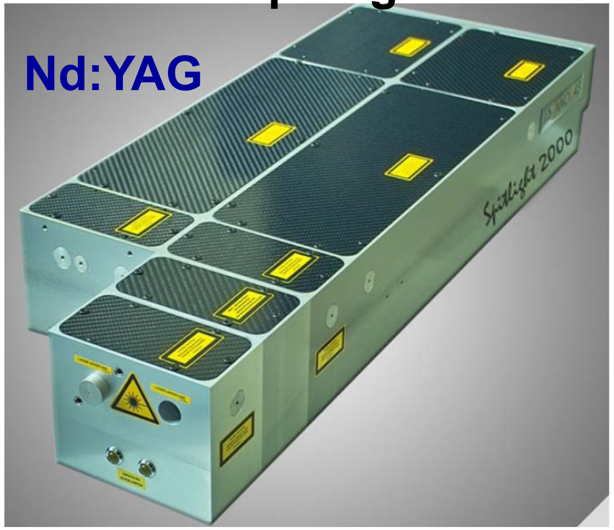
S/XB=2 for CII emission line for $n_e=10^{21}$m-3 and T_e=3eV in the ITER divertor.

an excellent photoelectron statistic $1/\sqrt{N_{el}} \ll 1\%$

New lasers will be used from middle of December 2010

7ns-pulse laser

InnoLas SpitLight 2000-10



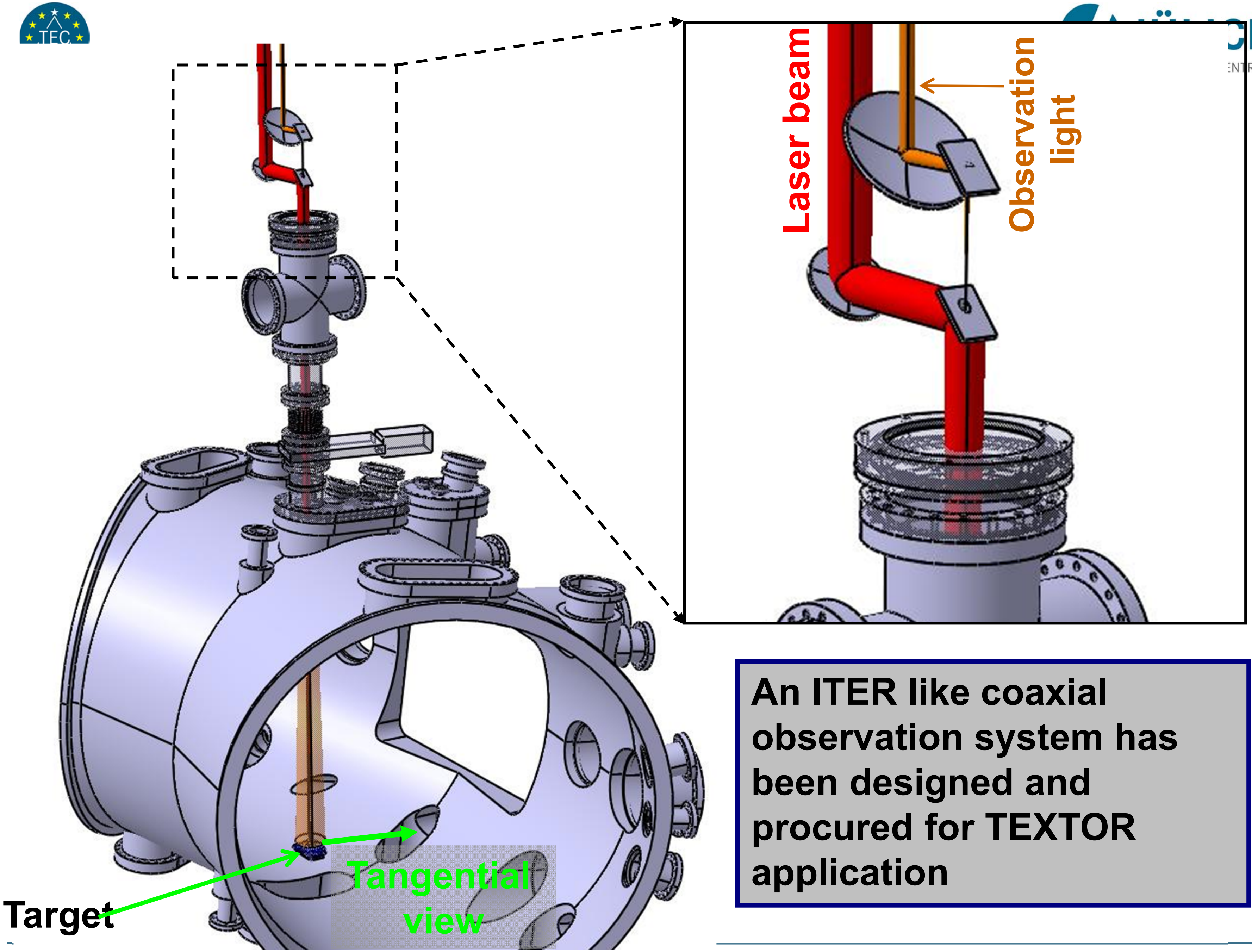
Wavelengths: 1064 nm, 532nm, 355
Pulse width: 7ns
Repetition rate 10Hz
Pulse energy 2,5 J at 1064 nm;
1,2 J at 532 nm;
540 mJ at 355nm.
Divergence <0.5mrad

35ps-pulse laser

TOPAG L2241/SH/TH

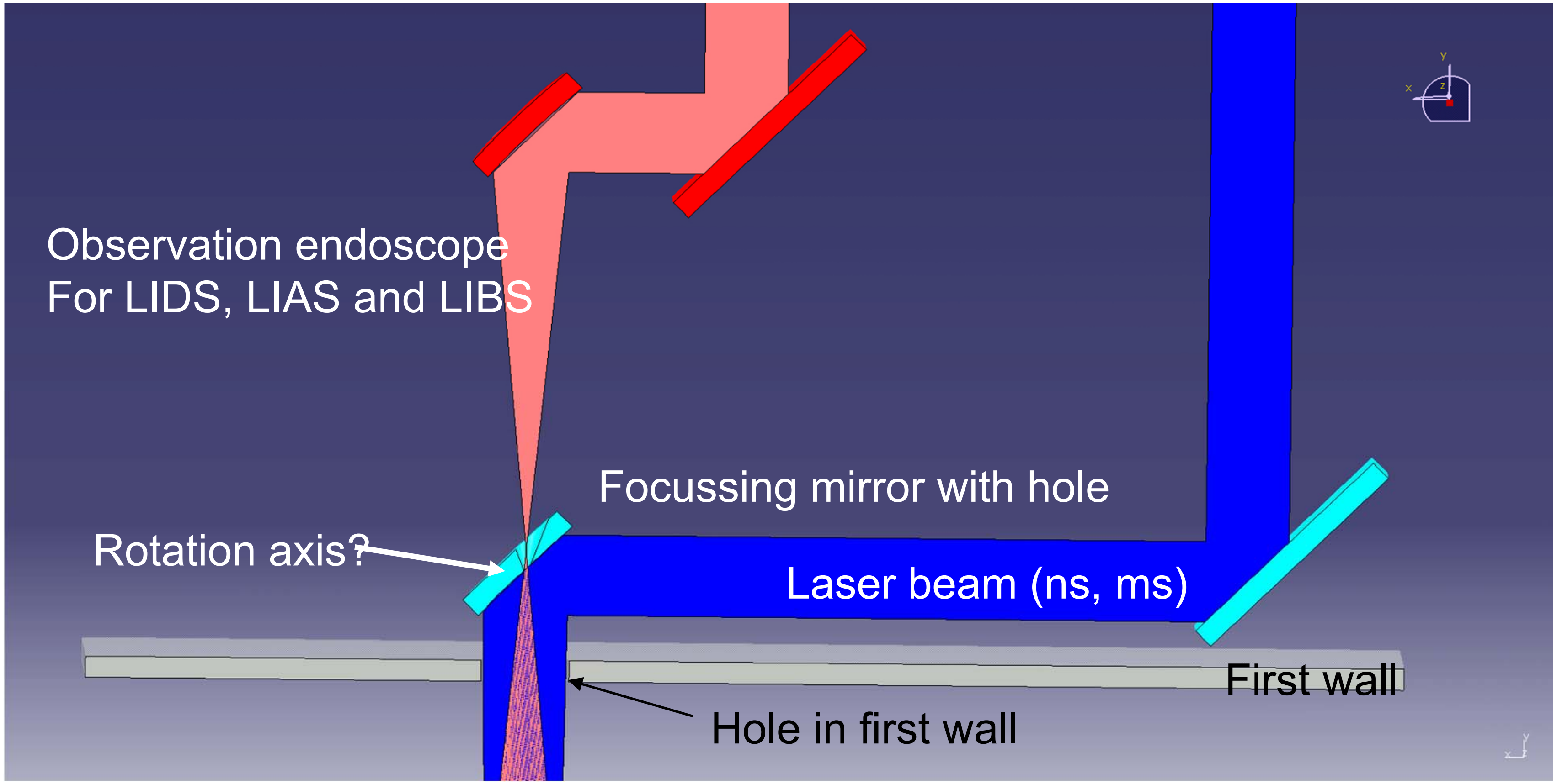
Wavelengths: 1064 nm, 532nm, 355
Pulse width: 35ps
Repetition rate 10Hz
Pulse energy 100mJ at 1064 nm;
50mJ at 532 nm;
30 mJ at 355nm.
Divergence <0.5mrad

Mirror based light guide into TEXTOR and alternatively in target chamber under construction



An ITER like coaxial observation system has been designed and procured for TEXTOR application

Details of the optical arrangement



Summary status and future work

LIDS is qualified to a high degree for ITER application, with some remaining issues

LIBS and LIAS have been intensively analysed in lab experiments

- amount of ablation
- composition, angular and energy distribution
- reproducibility
- on C bulk and C deposits up to 20 microns

LIBS data have been analysed depending on laser energy, for C bulk and thick C deposits (but only for 15 ns RUBY laser conditions)

An ITER like coaxial observation system has been designed and procured for TEXTOR application in 2011

B2-Eirene modelling has been performed for LIDS under ITER standard conditions

To be done

LIDS:

use of the ITER like coaxial observation
laser desorption physics from W,Be deposits

LIBS and LIAS:

Lab: Compare ns versus ps laser with respect to signal stability

Tokamak:

Demonstrate systematically LIBS and LIAS in a tokamak environment with an ITER like laser injection and observation system
Quantify both the amount of hydrogen and composition and amount of deposits with LIBS and LIAS under tokamak like conditions (distances, magnetic field,..) on well characterised samples, including mixed layers with the ITER material mixes, to replace Be by a Be like substitute, like Al or Mg.

Evaluate both the limitations of the measurement both with respect to the lower detection limit and the systematic scatters

Design, based on the gained experiences, a prototype like ITER system.

Two new lasers have been procured by FZJ to perform LIDS in Magnum PSI and FZJ PSI-2 linear plasma device for hydrogen retention detection in PWI studies (≈ 200 kE)

Work will start in 2011