ICTP/IAEA *Workshop on Plasma Physics: Capacity Building in Plasma Applications and Diagnostic Techniques*
7 – 11 March 2005

EUROPEAN USER FACILITY PALS
(Prague Asterix Laser System)

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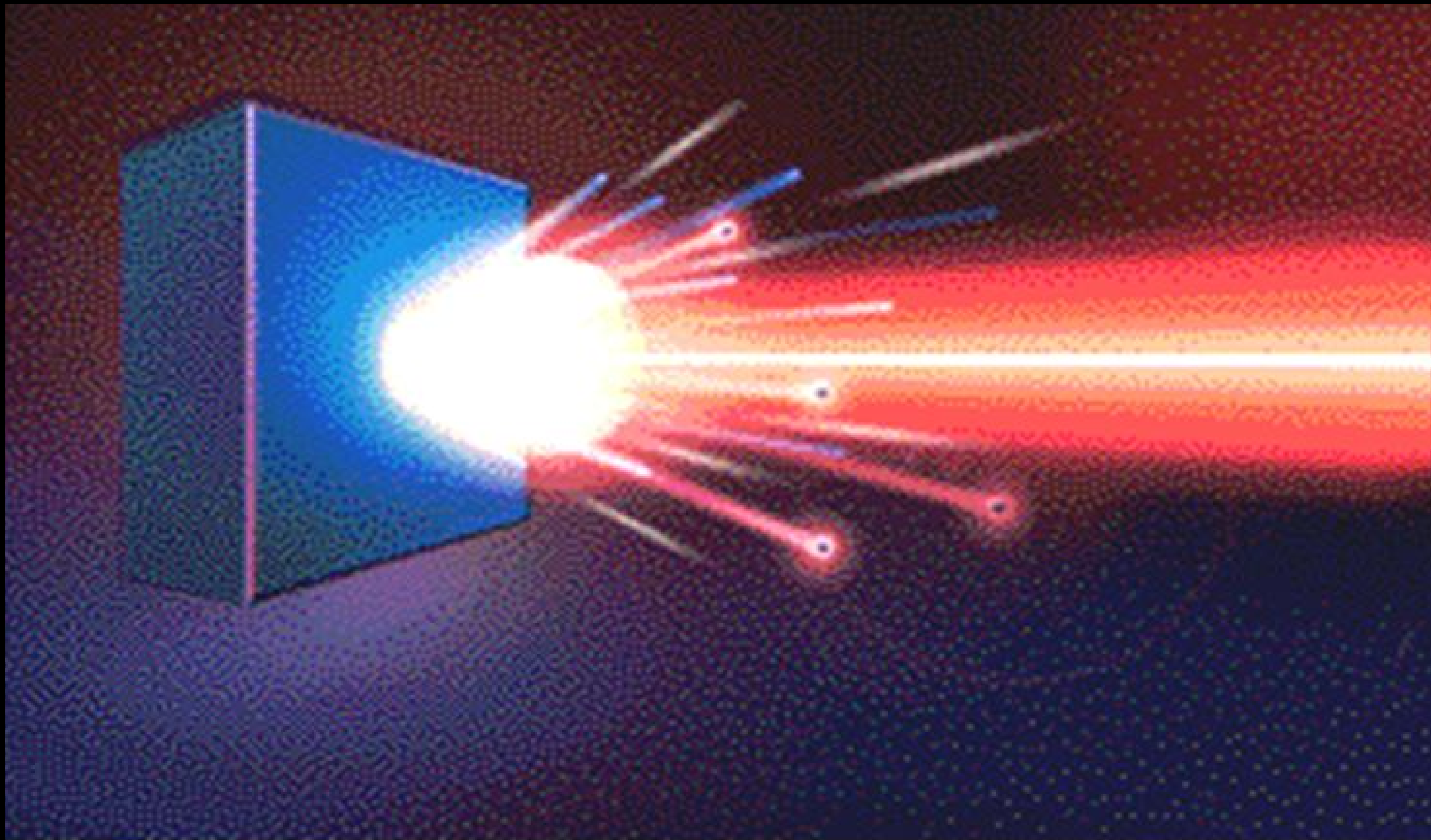
Na Slovance 2, Prague 8-Libeň, 182 21 Czech Republic
and
of the Institute of Plasma Physics (IPP) of ASCR
Za Slovankou 6, Prague 8-Libeň, 182 21 Czech Republic
& **PALS users**

Pictures and animations courtesy of J. Ullschmied, B. Rus, P. Straka, C. Kozák.

Focusing the laser beam on a (slab) target
Repetition rate of PALS accelerated 500 ×,
the real repetition rate ~30 minutes



Utilisation of pulsed kJ-class lasers in science & technology:

Experiments with the plasma produced on solid-state and gas-puff targets by focused high power laser beams

Study of interaction of intense laser radiation with matter

PALS is the Joint Research Laboratory between IP and IPP of ASCR

Key facilities:

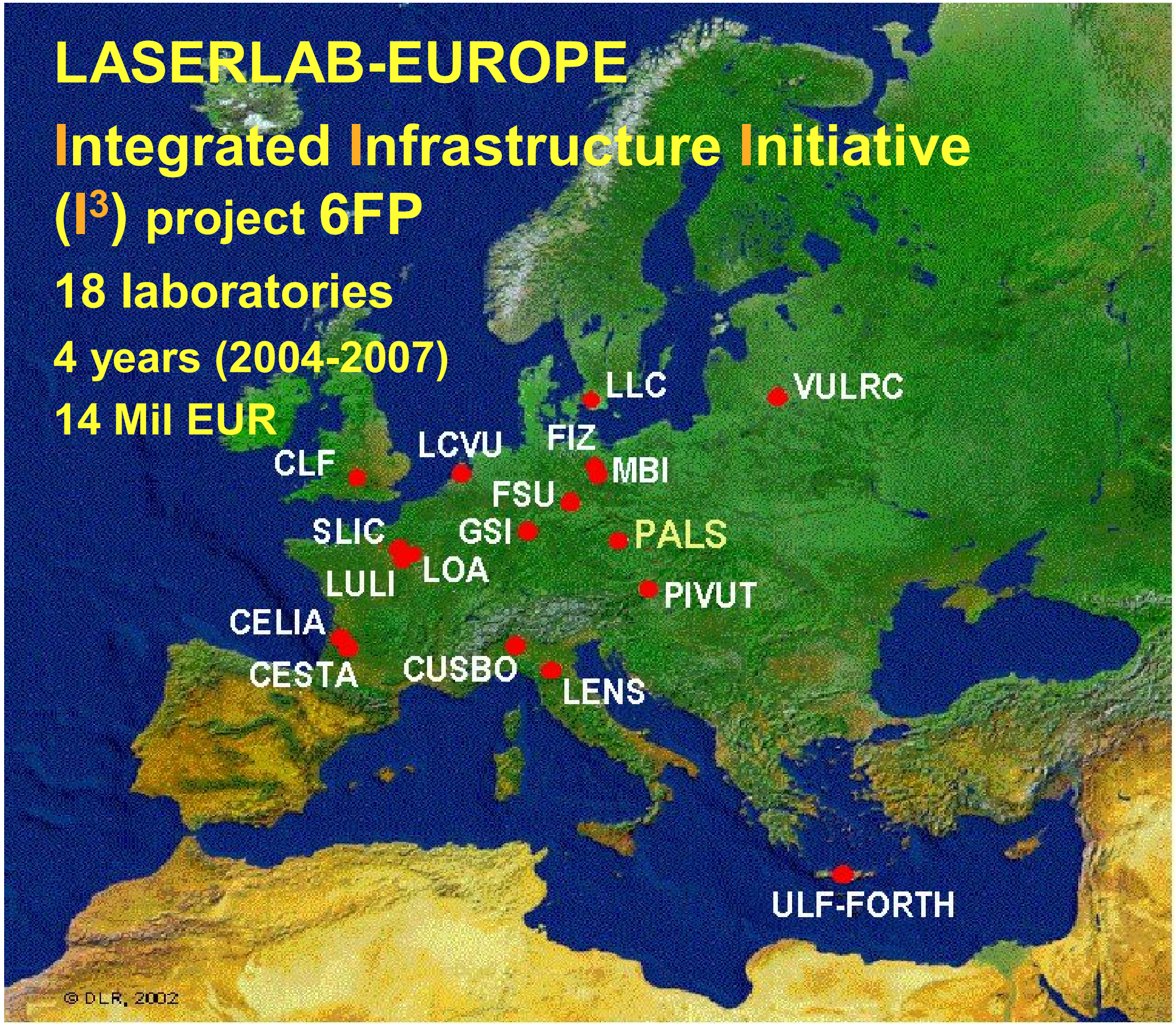
- ***3-TW iodine laser system PALS***
- ***100-MW Zn soft x-ray laser PALS-X***
- ***25-GW hybrid laser SOFIA***

PALS

INSTITUTE OF PLASMA PHYSICS
ACADEMY OF SCIENCES OF THE CZECH REPUBLIC

Fyzikální ústav Akademie věd ČR

PALS partners



www.laserlab-europe.net

The project includes:

Access to the laser facilities, incl. PALS

Joint Research Activities:

- **ultra-fast optics**
- **ultra-high power**
- **incl. OPCPA**

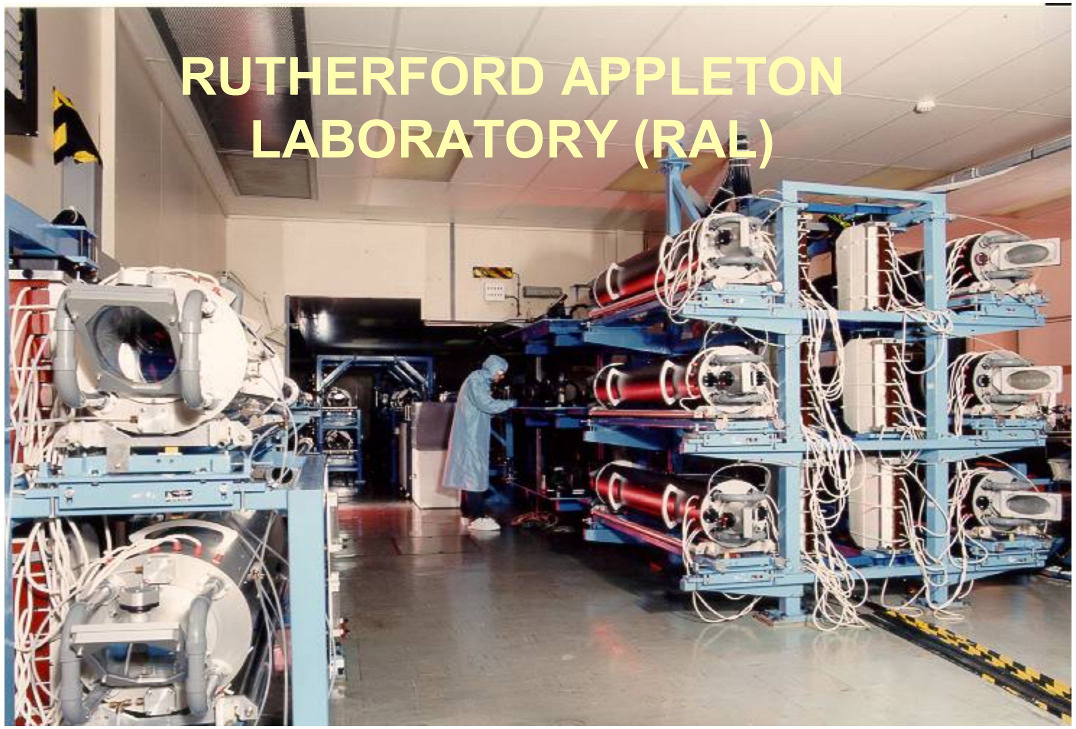
Networking & administration

Virtual Internet integrated laser laboratory

Training of students

In parallel:

PALS Marie-Curie Training Site



VULCAN

Nd:glass, 6 beams, 1054 nm

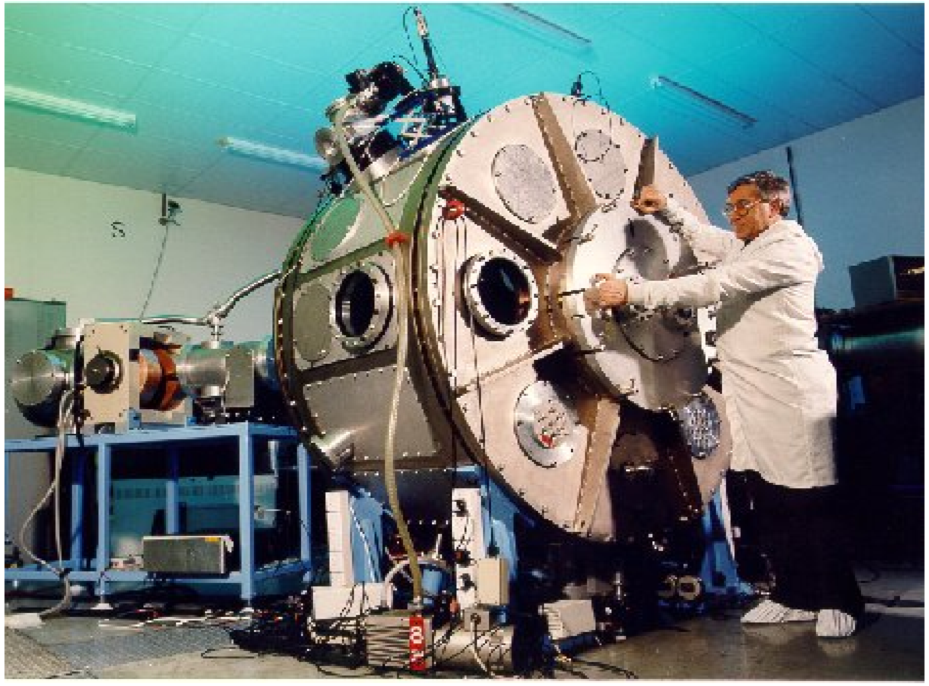
TW beam line:

2.6 kJ, 1 ns, 3 TW

Sub-ps CPA module:

> 100 TW

~10^{20} Wcm^{-2} on target



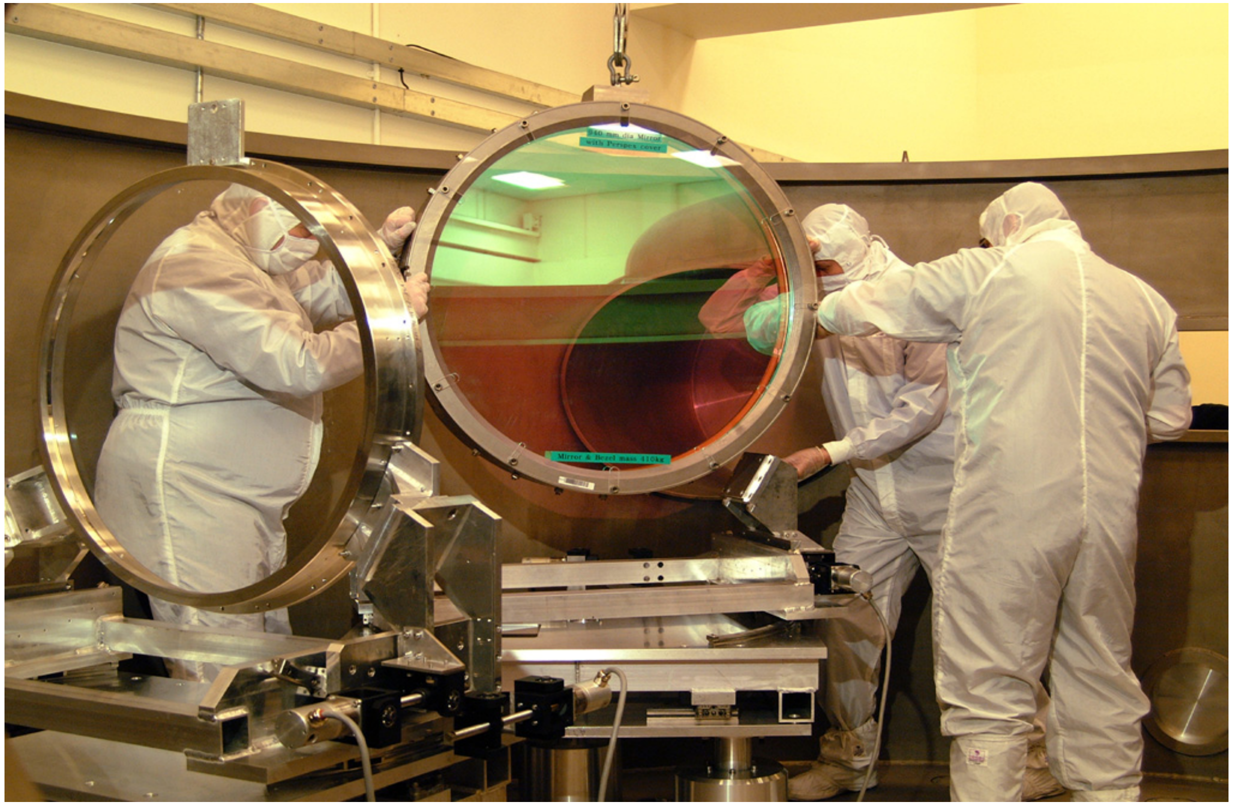
PETAWATT UPGRADE

October 2002

OPCPA module

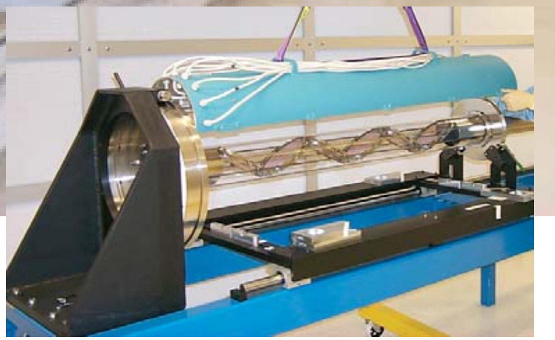
423 J, 410 fs

1.06 x 1021 Wcm-2 on target



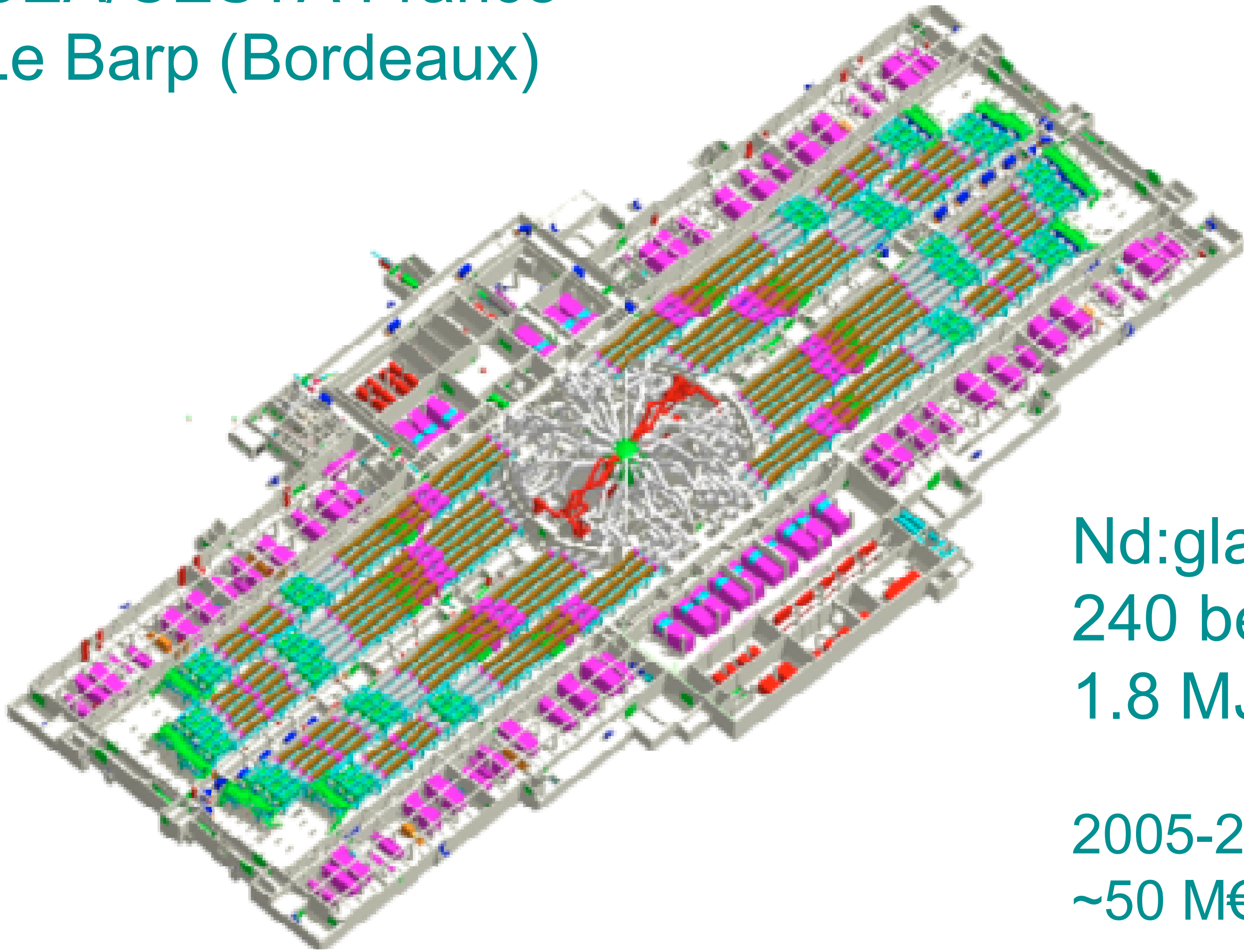
LABORATOIRE pour l´UTILISATION des LASERS INTENSES (LULI)

LULI 2000
Nd:glass
2 beams
2 kJ, 1.3 ns



LULI 100 TW CPA line
Ti:Saphire (Nd^{3+})
300 J, 30 fs

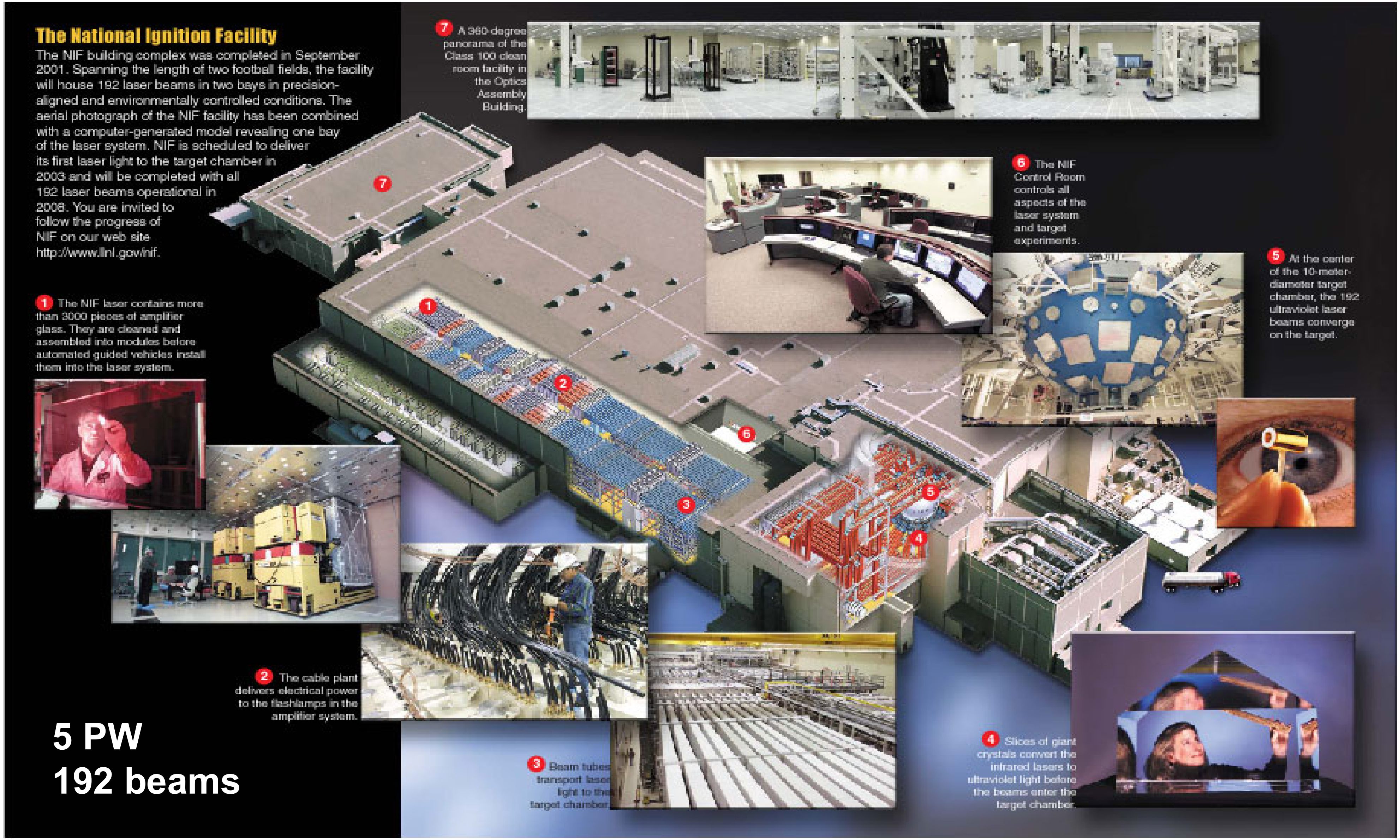
LASER MEGAJOULE
CEA/CESTA France
Le Barp (Bordeaux)



Nd:glass (3ω)
240 beams
1.8 MJ, 600 TW

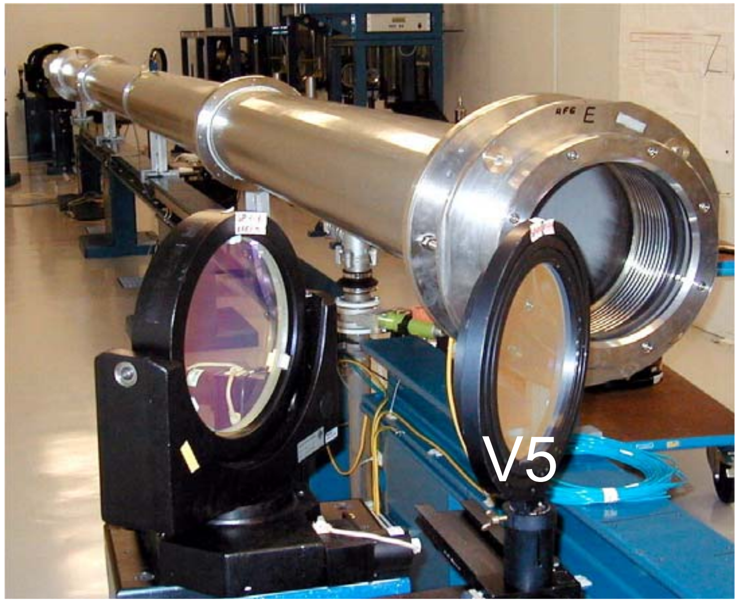
2005-2010
~50 M€

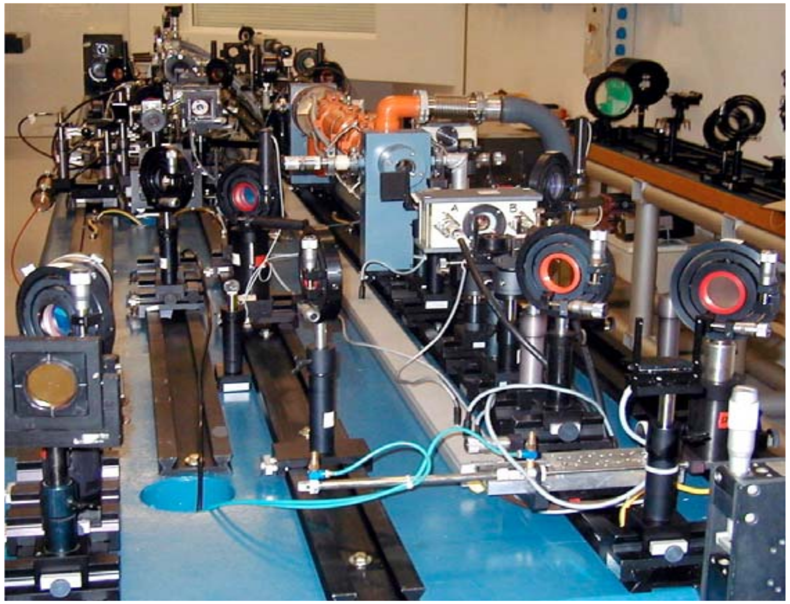
NATIONAL IGNITION FACILITY (NIF)



NIF TARGET CHAMBER

PALS history and characteristics





PALS ***history and characteristics***

Place of birth : MPQ Garching, Germany

Transfer to Prague : 1997-1998

Reassembling of the system finished in autumn 1999

Operational tests : November 1999 – May 2000

Launching : 7 June 2000

Users experiments since September 2000

Basic characteristics:

Pulsed single beam iodine photodissociation laser

Fundamental wavelength: 1ω = 1315 nm (infrared)

Red, blue and UV harmonic beams

Pulse duration:	~ 0.4 ns
Output beam diameter:	290 mm
Output energy at 1ω:	10 J - 1 kJ

PALS unique features

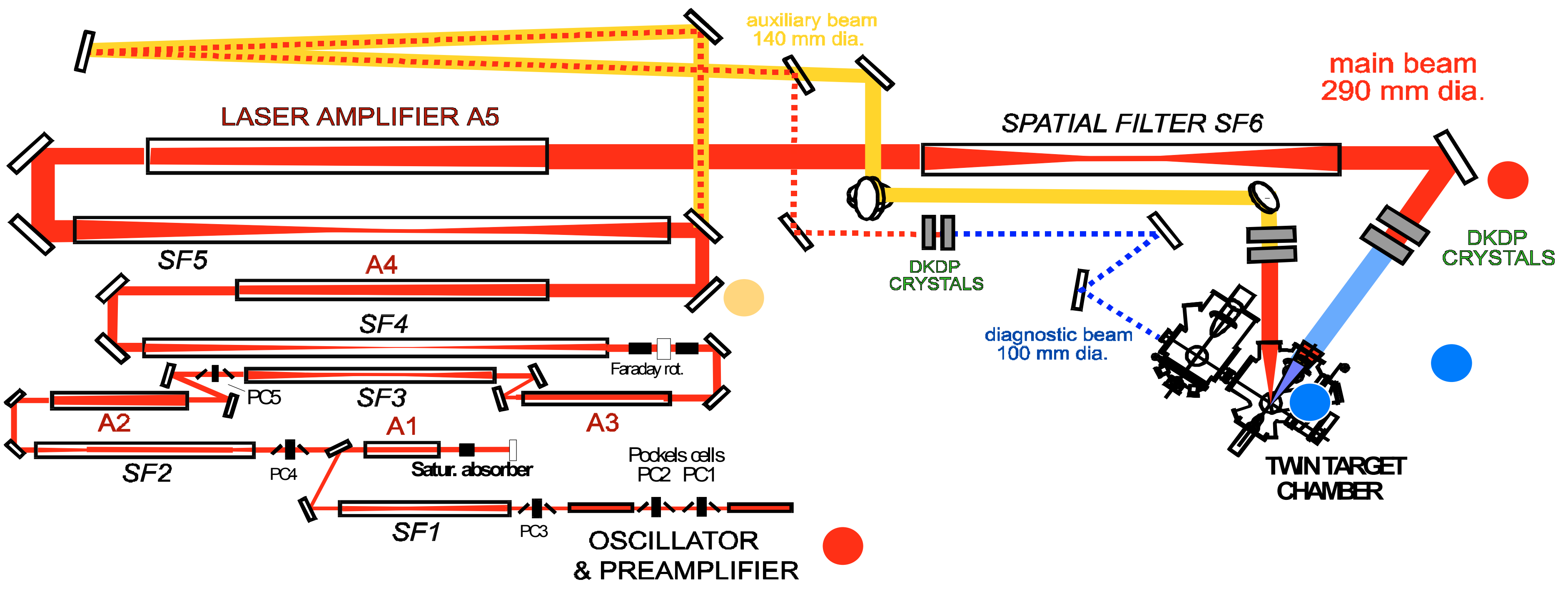
- iodine gas laser, working wavelength 1315 nm

- laser of the highest energy in Europe in a single beam configuration

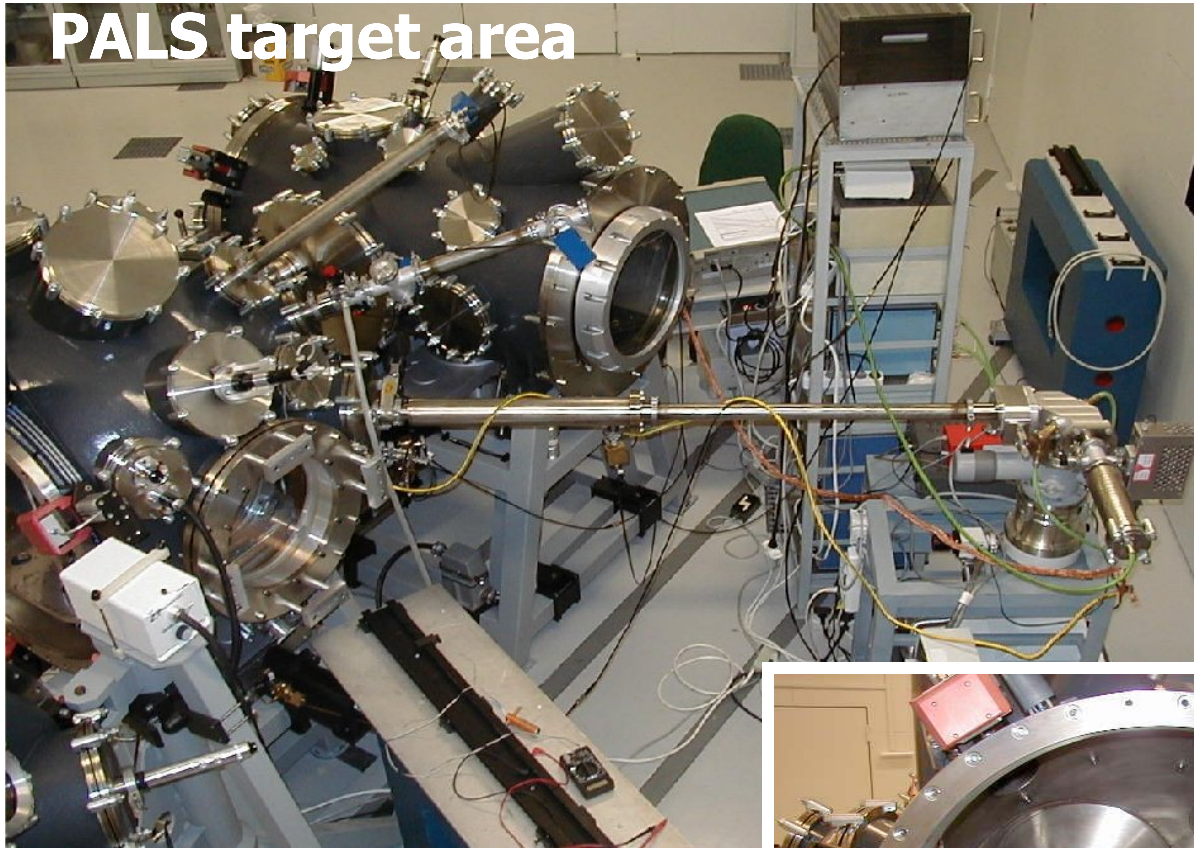
6 gas laser amplifiers + 6 spatial filters

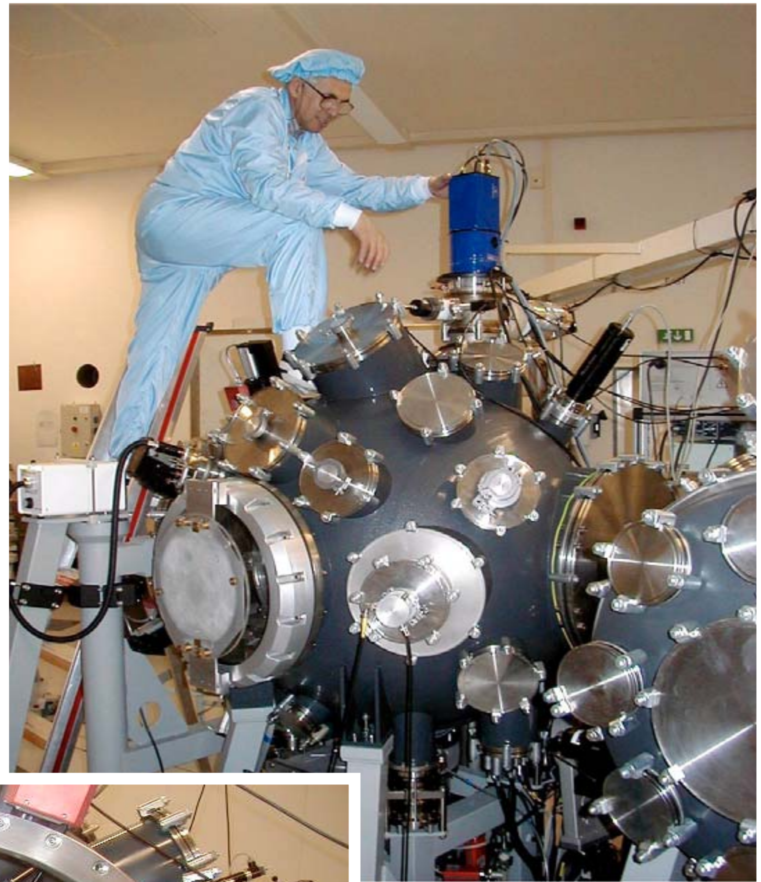
Main, auxiliary and diagnostic different-color beam lines

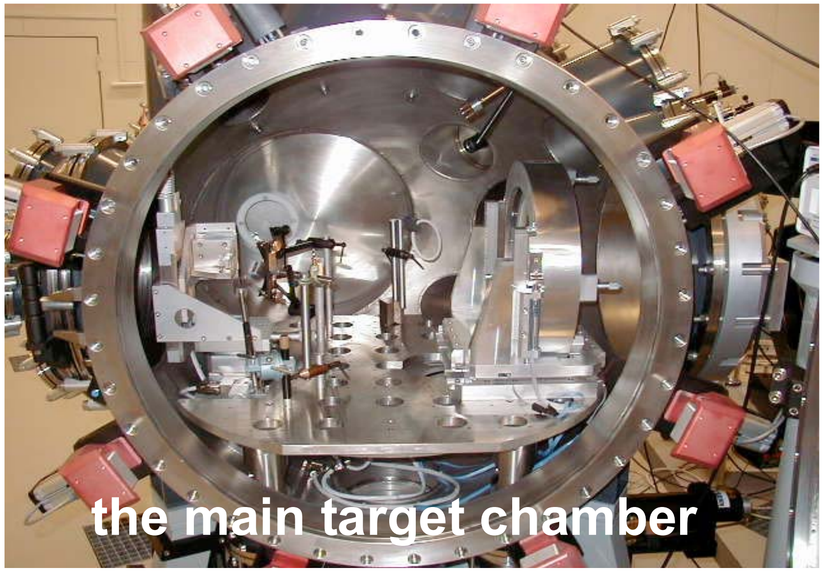
Schematic of the laser beam lines



PALS target facilities







PALS target facilities

Unique twin target chamber

Achievable power density at the target > 10^{16} W/cm^2

Several different-colour laser beam lines

Both point and linear focusing optics available

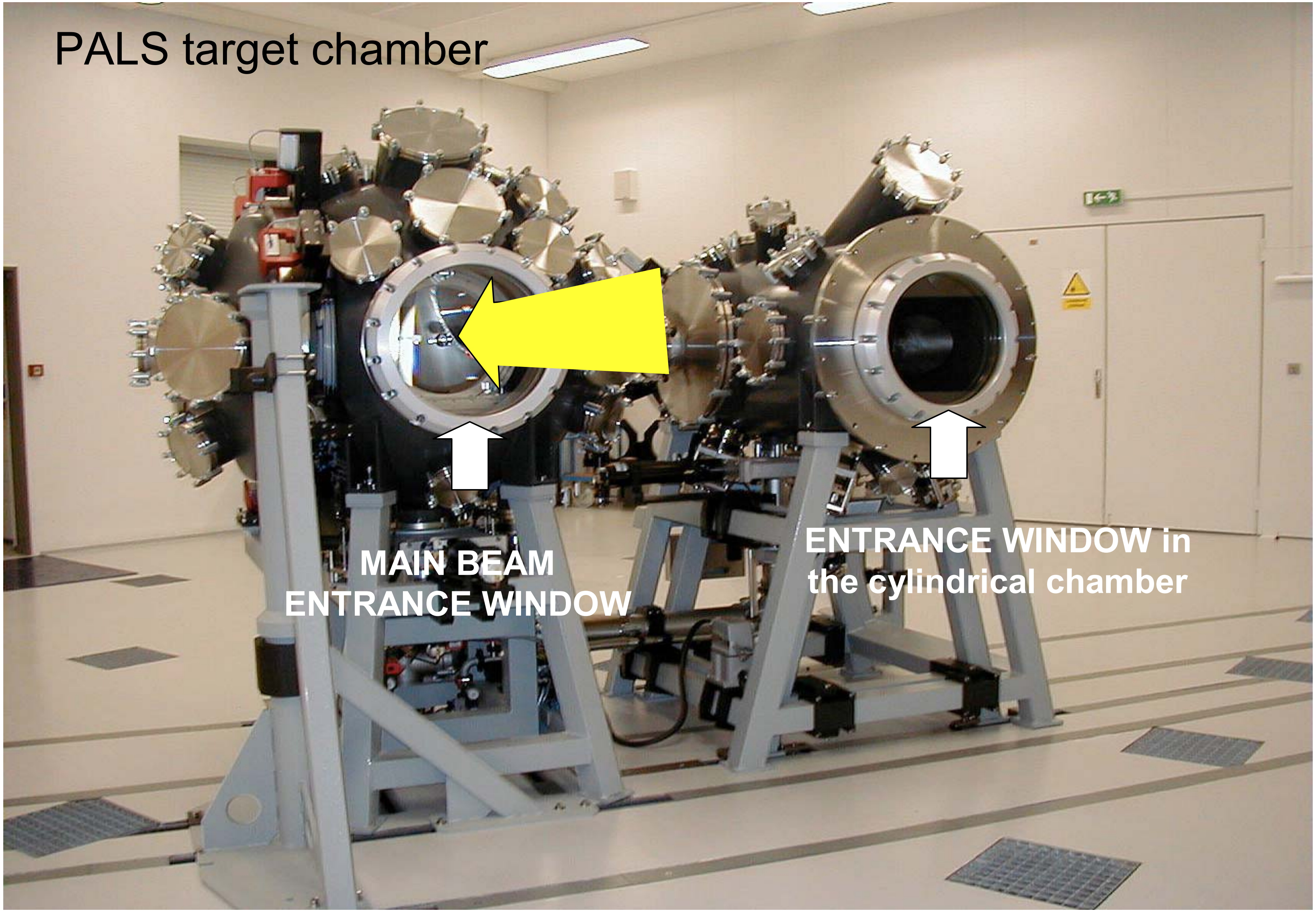
Advanced equipment for ion and x-ray diagnostics

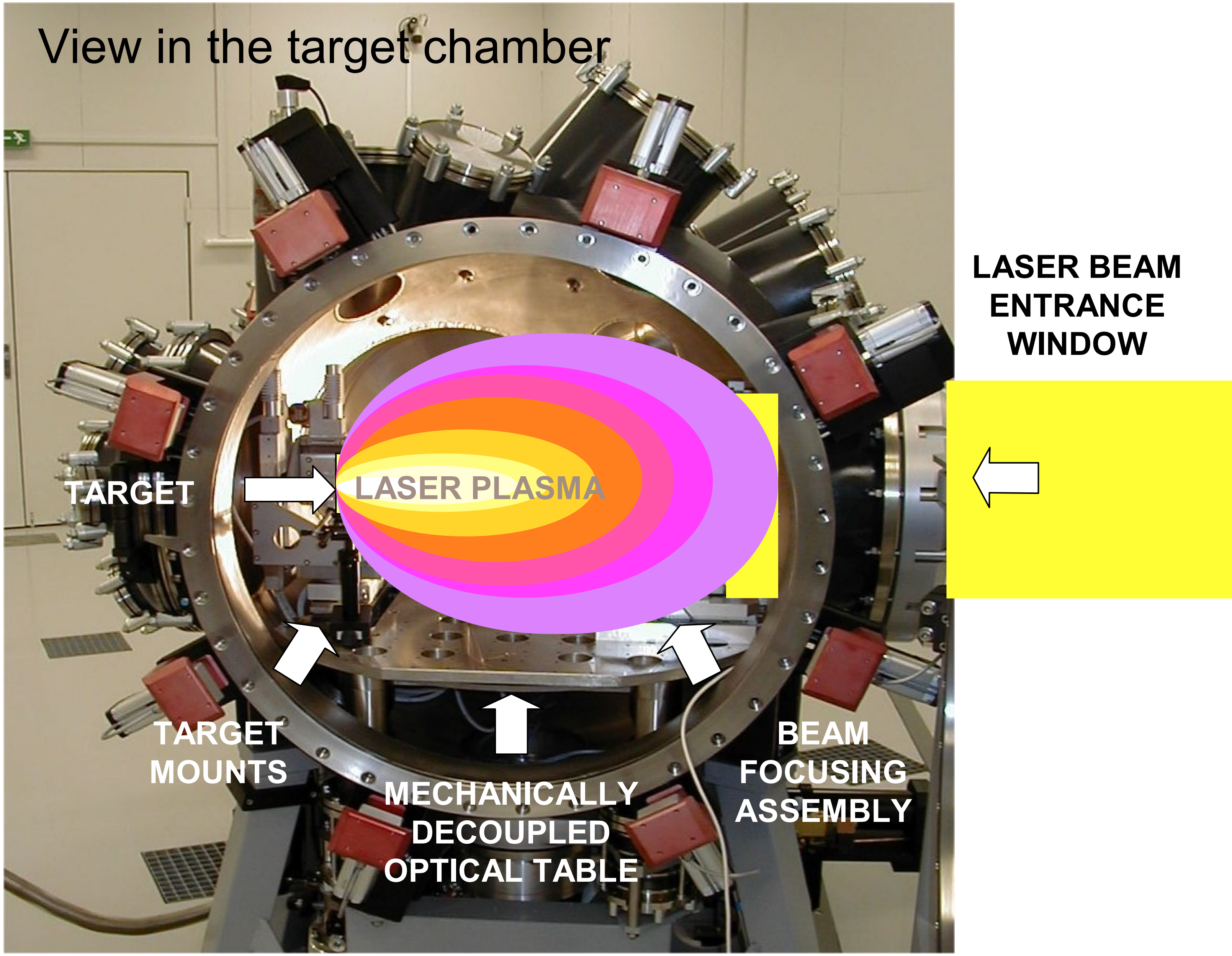
Arrangement for x-ray laser experiments

Equipment for shock wave studies


V5
V2
RF2
to RF6
RF1
V1
SA
RF3
RF5
PZ2
V4
RF4
VV
PZ
V3
PZ1
PZ0
OSC
YAG
PALS laser hall

PALS main beamline output end


PALS target chamber
MAIN BEAM
ENTRANCE WINDOW
ENTRANCE WINDOW in
the cylindrical chamber



View in the target chamber
LASER BEAM ENTRANCE WINDOW
TARGET
LASER PLASMA
TARGET MOUNTS
MECHANICALLY DECOUPLED OPTICAL TABLE
BEAM FOCUSING ASSEMBLY

There are thousands of things one can do with a nanosecond high power laser:

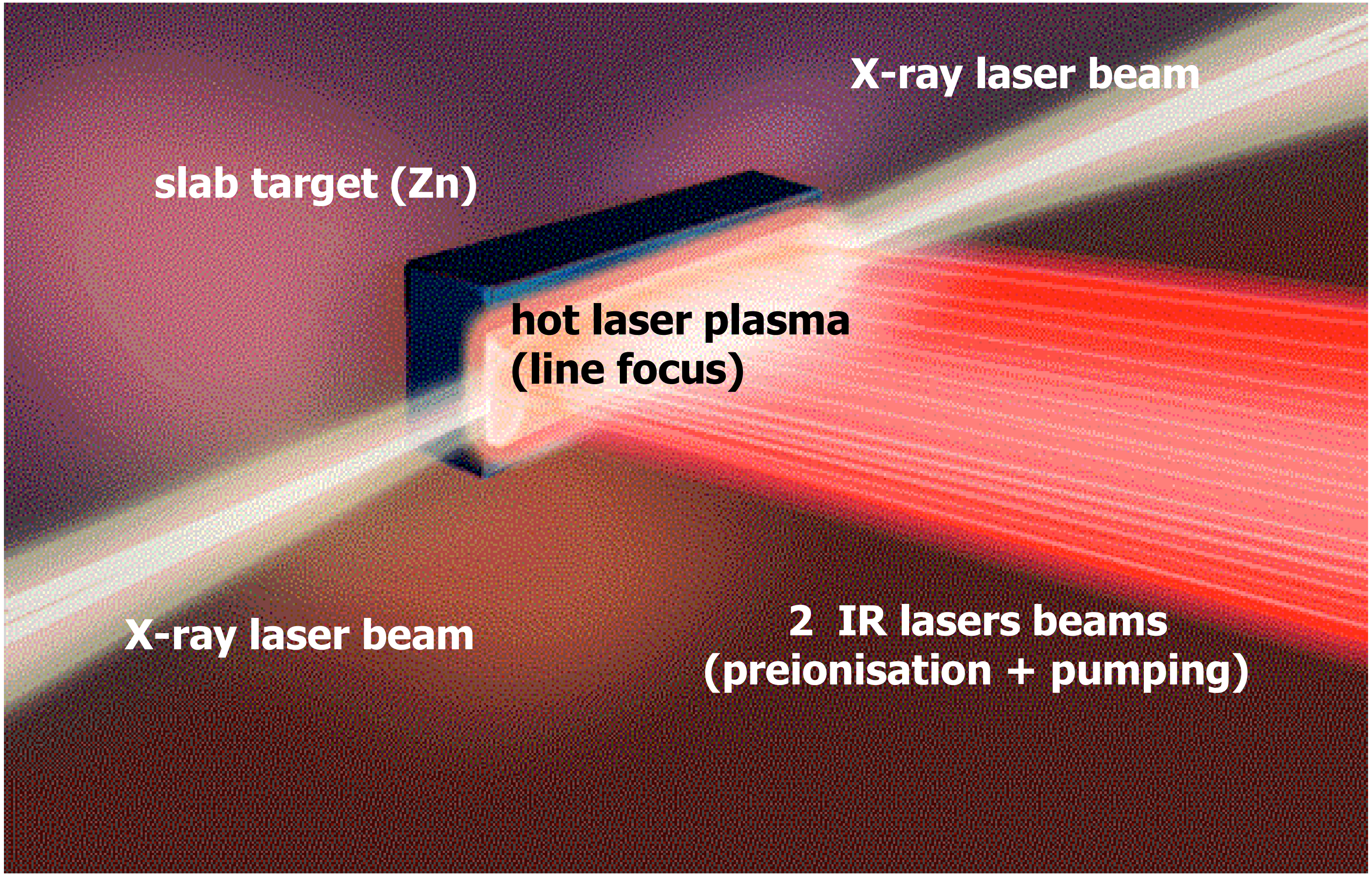
-XUV spectrometry
-fusion related experiments
-generation of shock waves
-incoherent X-ray sources
-ion sources
-impact studies
etc

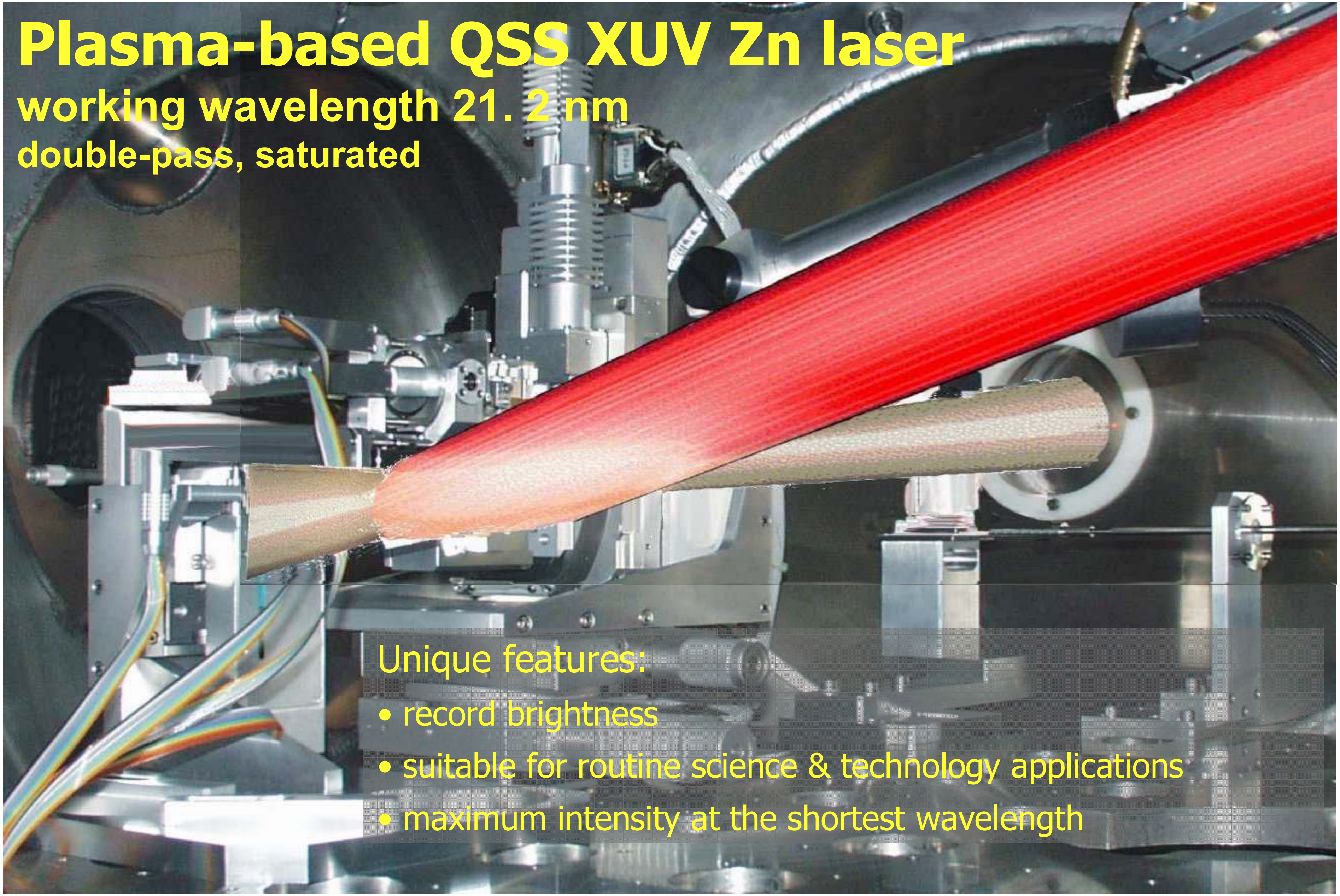
BUT the new science is to be sought either in the domain of *short wavelength* or *ultra short high intensity pulse*

How to get into the domain of short wavelength?
Operate a sufficiently intense X-ray laser

PALS

Generic scheme of an x-ray laser experiment

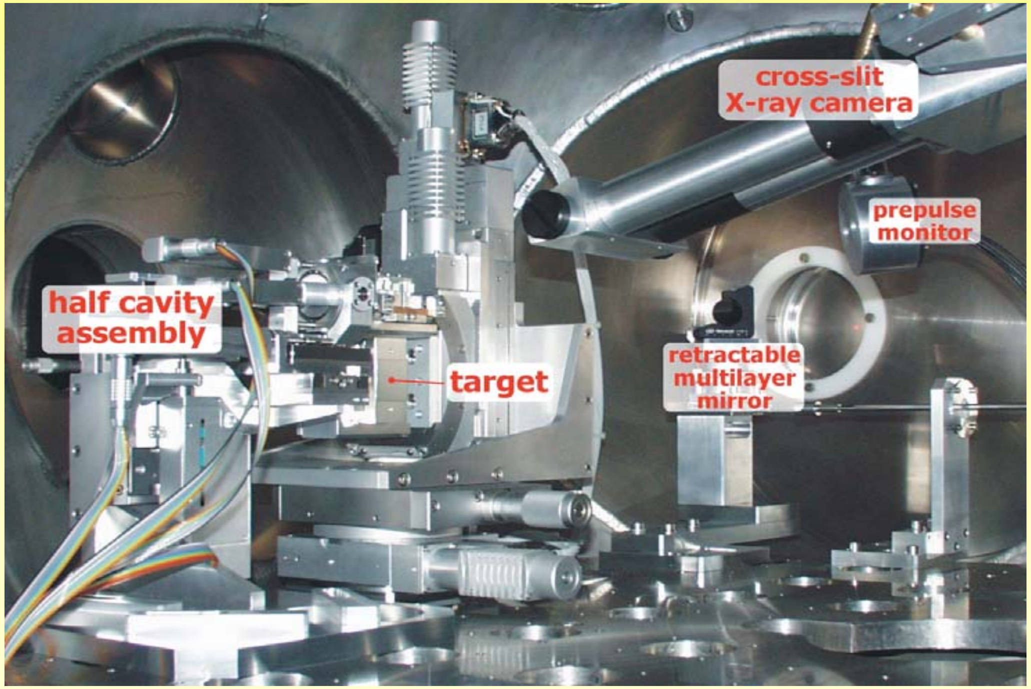


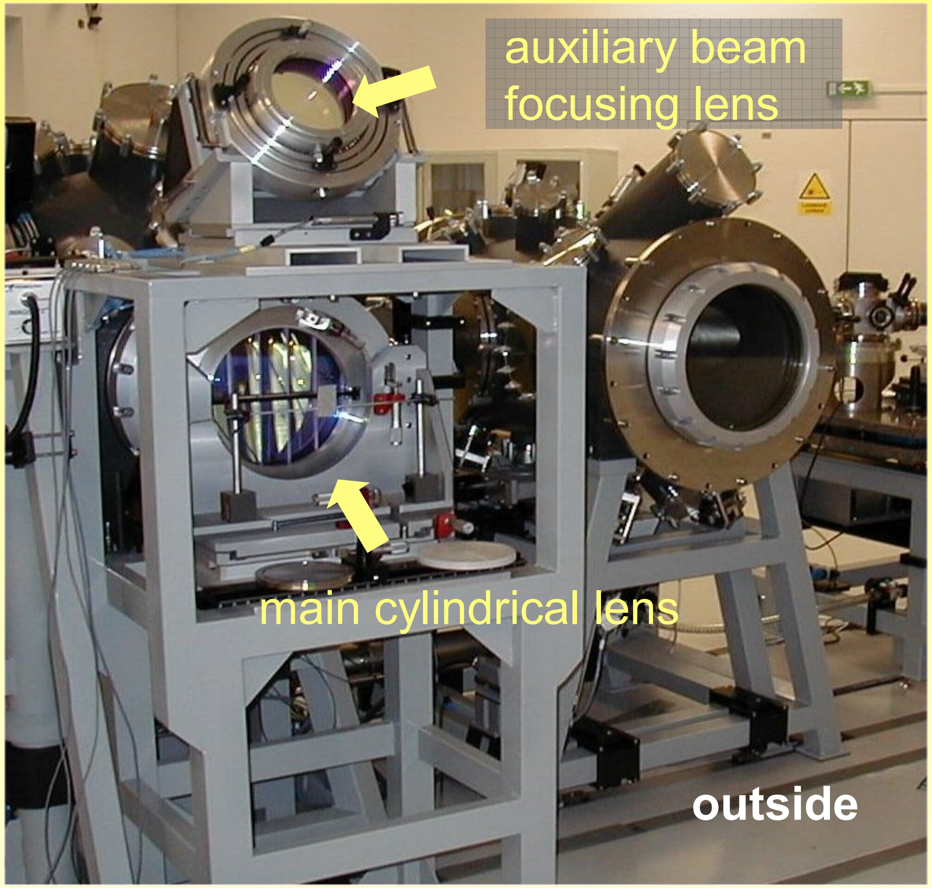

Plasma-based QSS XUV Zn laser
working wavelength 21. 2 nm
double-pass, saturated
Unique features:
• record brightness
• suitable for routine science & technology applications
• maximum intensity at the shortest wavelength

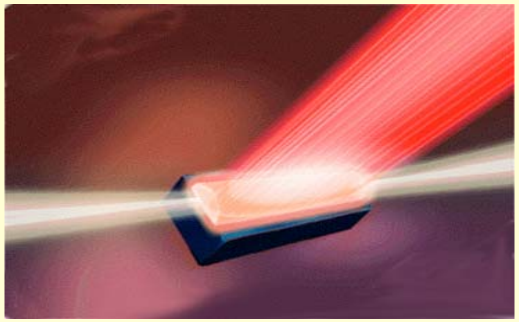
Saturated double-pass XUV laser on Ne-like zinc
at 21.22 nm (58.53 eV)

Launched June 2001
Optimised November 2002

Experimental arrangement

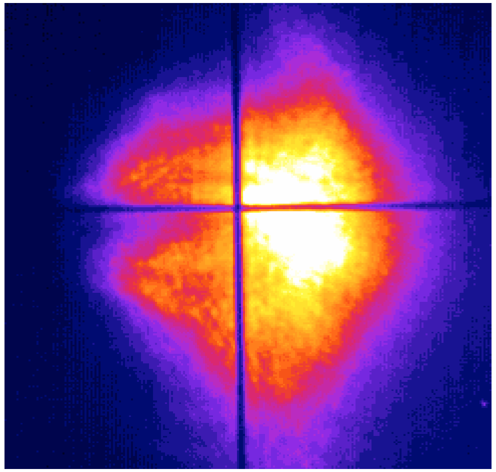




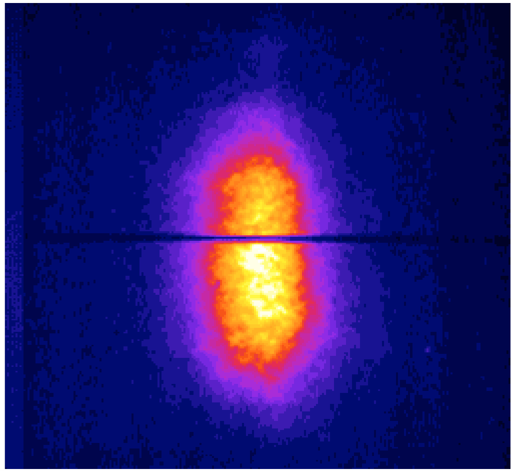


main beam 600 J
auxiliary beam 1,5 J

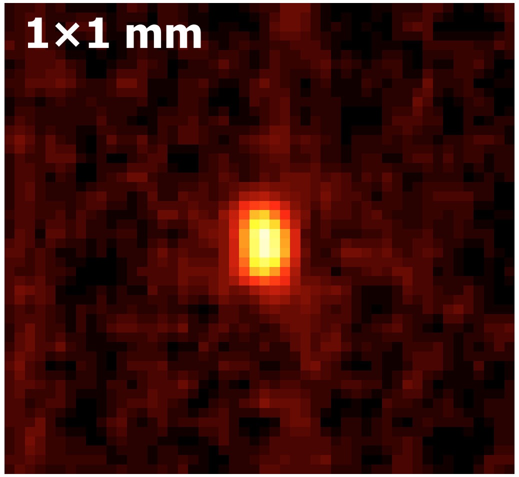
Development of the PALS-X XUV laser



div. 3.5x5.5 mrad Δt = 10 ns (2001)



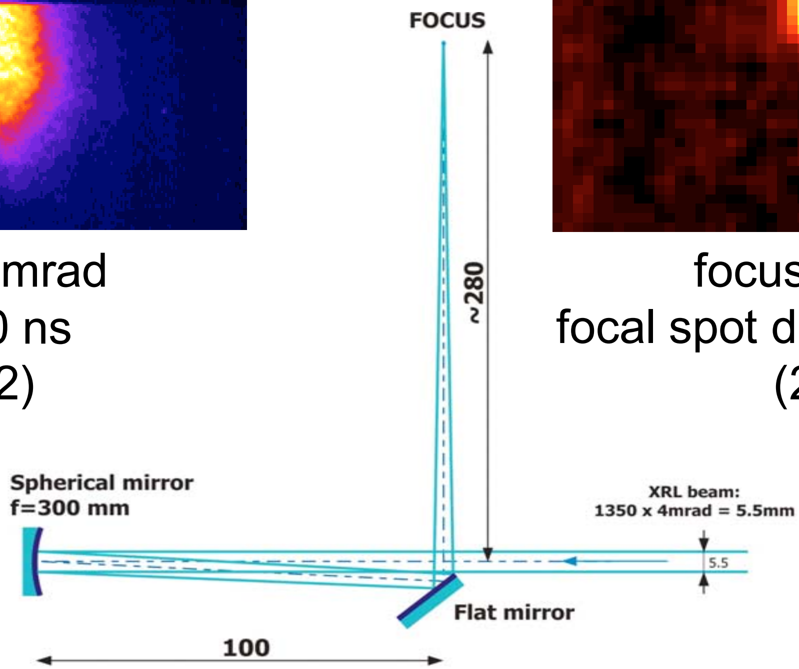
div. 1x4 mrad Δt = 50 ns (2002)



focused beam
focal spot diameter ~50 μm
(2004)

Pulse duration 80 - 100 ps
Beam energy 4 - 10 mJ
Pulsed power 40 - 150 MW

Brightness
> 3.10^{27} phot. s^{-1} mm^{-2} $mrad^{-2}$



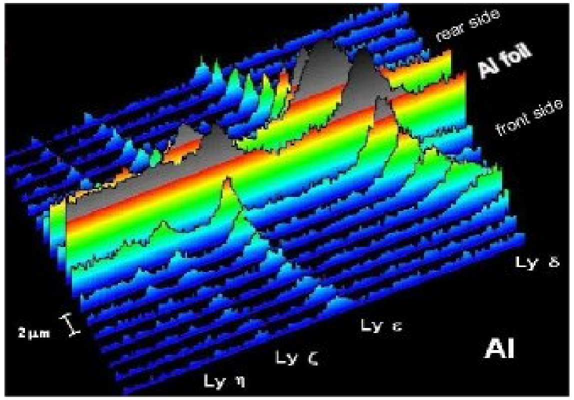
Focal intensity ~ 4×10^{10} Wcm^{-2}

PALS

A users facility providing transnational access

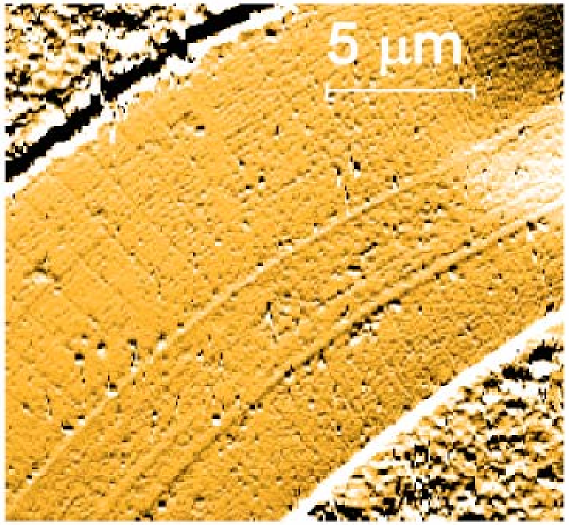
25 users projects completed since IX 2000

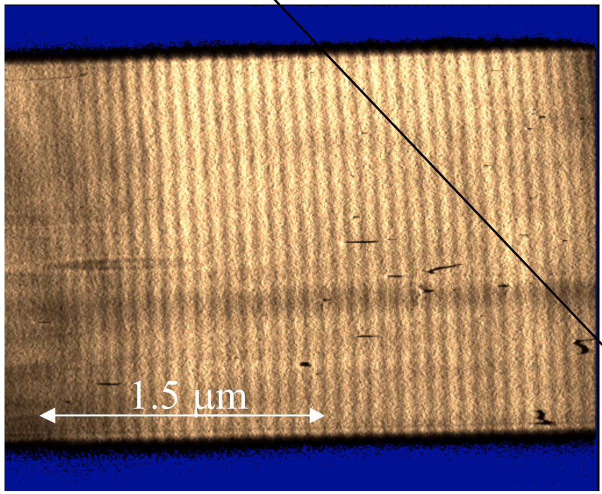
12 new projects are ahead



Laser soft x-ray sources

Time- and space-resolved x-ray spectroscopy

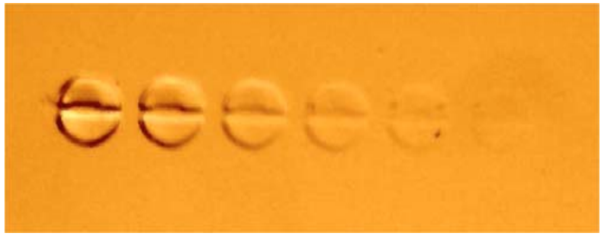




Contact XUV microscopy

XUV interferometry of surfaces

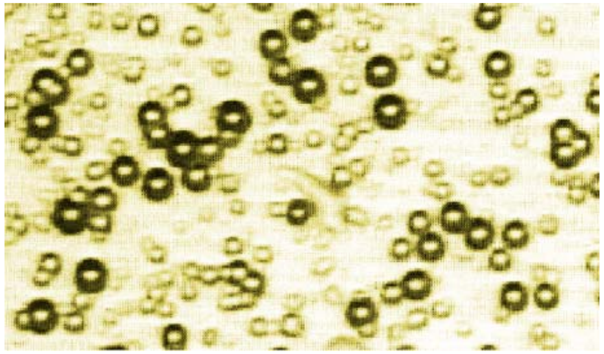
XUV ablations studies



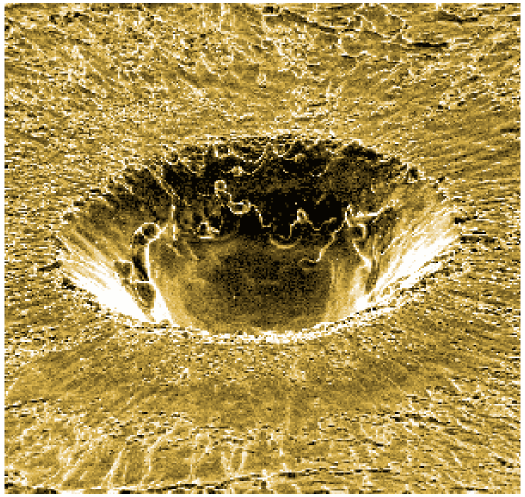
Neon-like zinc x-ray laser (21.2 nm)

the brightest XUV laboratory source ever built in

PALS

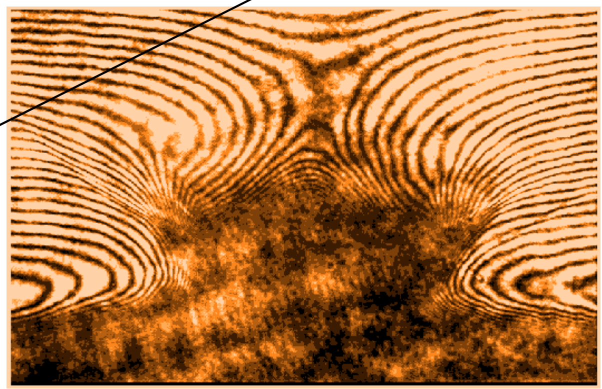


Ion implantation studies

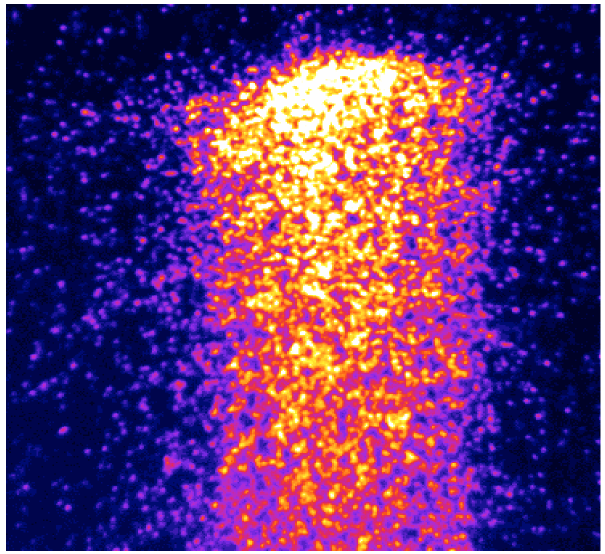


Crater formation studies

Laser ion sources



Multiframe laser interferometry



Shock wave studies

PALS co-laborators

PALS permanent staff:

K. Jungwirth, M. Bittner, M. Bodnár, A. Cejnarová, E. Horváth, L. Juha, J. Knyttl, J. Kovář, M. Kozlová, B. Králiková, J. Krása, E. Krouský, P. Kubát, L. Láska, P. Maroušek, K. Mašek, T. Mocek, M. Pfeifer, A. Präg, P. Prchal, S. Přeučil, O. Renner, K. Rohlena, B. Rus, P. Severová, J. Skála, V. Skálová, P. Straka, H. Turčičová, Z. Vančura, J. Zeman

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Hosting teams from France, Germany, Holland, Italy, Poland, Russia and CR:

G. Jamelot, H. Safa, D. Ros, A. Carillon, J.C. Lagron, D. Joyeux, D. Phalippou, J. Eric, F. Ballester, M. Kalmykov, B. Aune, M. Bousoukaya *(LSAI Orsay, CEA Saclay),* F. Bijkerk, R. De Bruijn, H. Kooijman *(IPP FOM Rijnhuisen),* D. Batani, A. Bernardinello, M. Tomasini, V. Masella, C. Lora Lamia Donin, T. Desai, G. Poletti, C. Olivotto, E. Henry, G. Luccini, A. Rovasio, H. Stabile, F. Strati *(Universita Milano-Bicocca),* L. Torrisi, S. Gammino,G. Ciavola, A. Mezzasalma *(Universita di Messina, INFN Catania),* H. Fiedorowicz, A. Bartnik, J. Wawer, A. Mikolajczyk, R. Rakowski *(MUT Warsaw),* E. Förster, P. Puhlmann, I. Uschmann, A. Lübke *(F. Schiller Universität Jena),* F.P. Boody *(Light Ion technologies Bad Abbach),* T. Wilhein, M. Wieland *(TU Remagen),* T. Pisarczyk *(IPPLM Warsaw),* F. Rosmej, J. Wieser, M. Schollmeier *(GSI Darmstadt),* J. Wołowski, L. Ryć, P. Parys, J. Badziak, A. Kasperczuk, A. Borodziuk, K. Bochenska *(IPPLM Warsaw),* A. Szydlowski *(IPJ Otwock-Swierk),* V. Kondrashov *(TRINITI Troick),* G. Tallents *(University of York),* S. Civiš *(ÚFCHJH AS ČR),* M. Kálal, J. Limpouch, M. Vrbová *(CTU Prague)*

57 different users made at PALS 107 visits of an average duration of 12 days and spent there till November 2003 1295 days

Research programmes at the facilities

PALS terawatt laser system

Laser-matter interaction at focused power densities $10^{14} – 10^{16}$ W/cm^2

- **laser-plasma dynamics**
- **ablation pressure studies (laser imprint smoothing)**
- **generation of shock waves (EOS studies at high pressures)**

Development and applications of

- **soft x-ray sources (XUV lithography, photo-etching, microscopy)**
- **laser ion sources (ion injection and implantation)**

QSS plasma-based XUV lasers

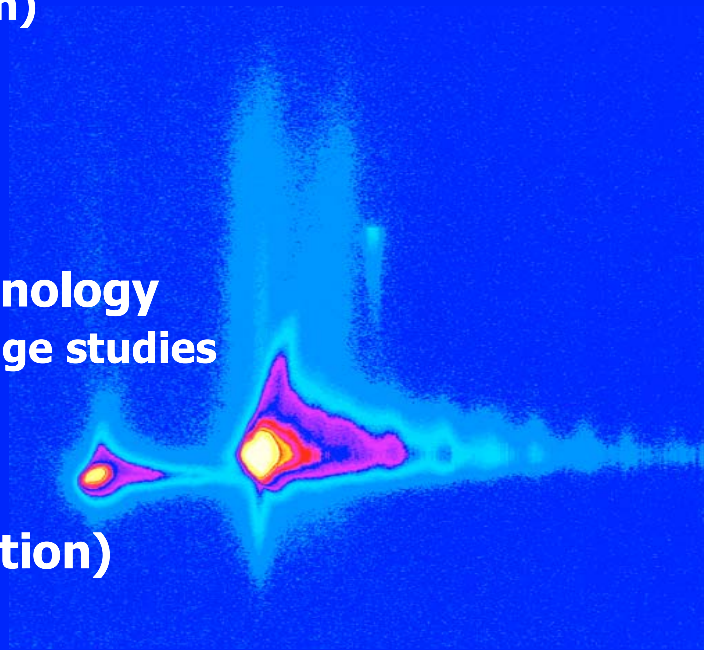
Testing new laser schemes

Application of XUV lasers in science and technology

- **interferometry, laser ablation & radiation damage studies**

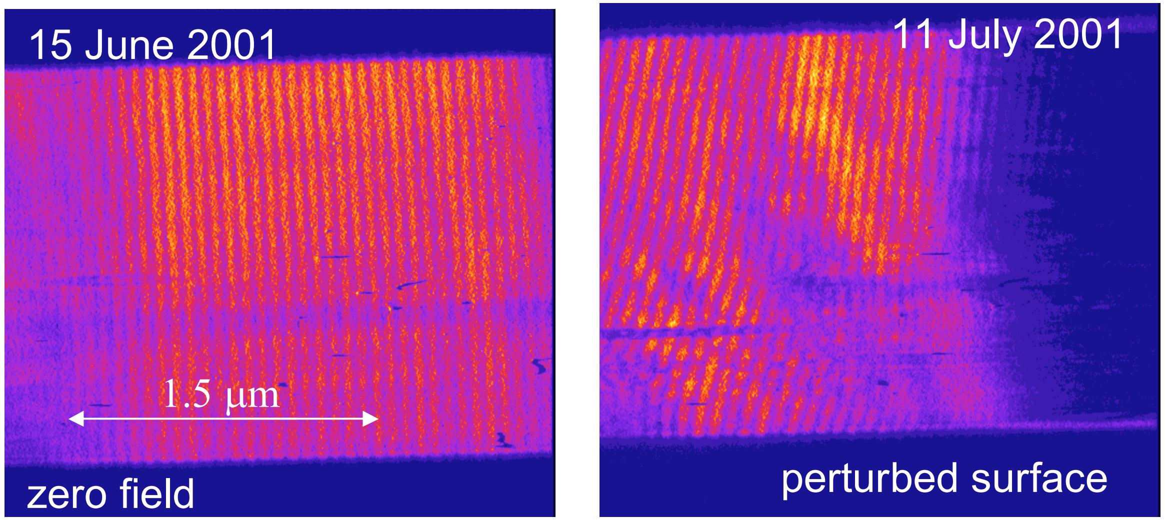
SOFIA

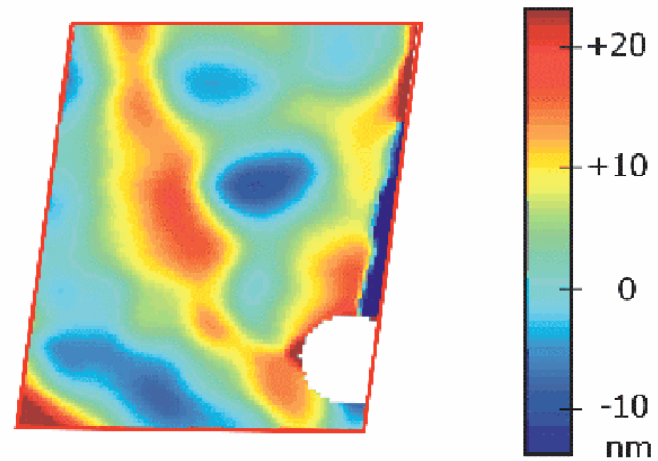
Generation of fs pulses (OPCPA implementation)



Applications of the zinc soft x-ray laser

Nanometric x-ray interferometry of surfaces





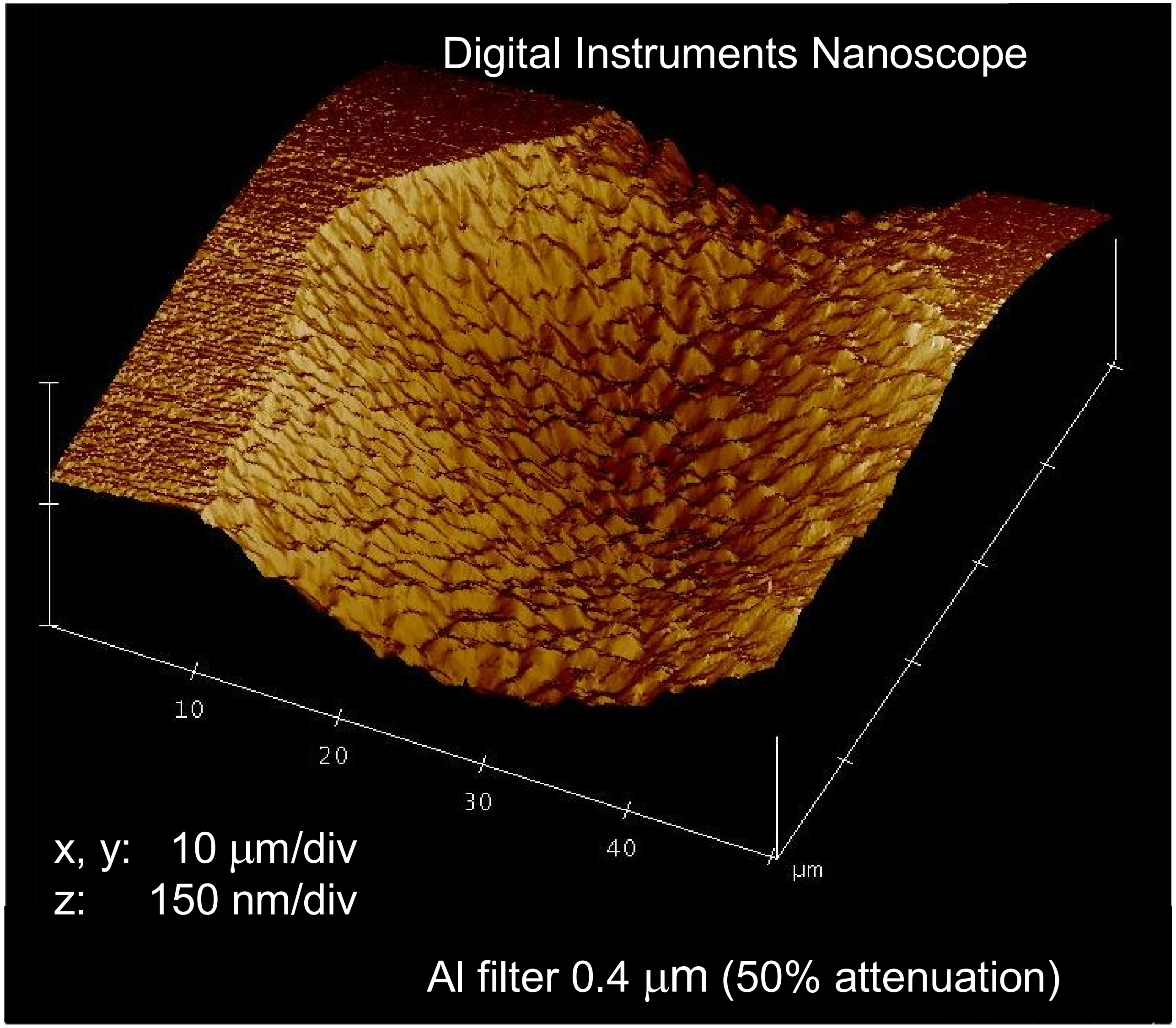
relief map of the perturbed surface at 50 MV/m

Fresnel grazing-incidence interferometer
(Zn laser, 21.2 nm)

Nanometric soft x-ray interferometry used for the first time for studies of pre-breakdown processes on Nb-coated electrode surfaces in strong electric fields (the main limiting factor at construction of charged particle accelerators).

Co-operation: LSAI (CNRS Orsay), IOTA (Univ. Paris Sud), CEA-SEA (Saclay)

XUV ablation studies with the PALS XUV laser (April 2004)



AFM image of the crater ablated in PMMA by a focused beam of the PALS XUV Ne-like Zn laser (21.2 nm).

To our knowledge, this was the first observation of material ablation and plasma production with a laser operating in the XUV region ($\lambda < 30$ nm).

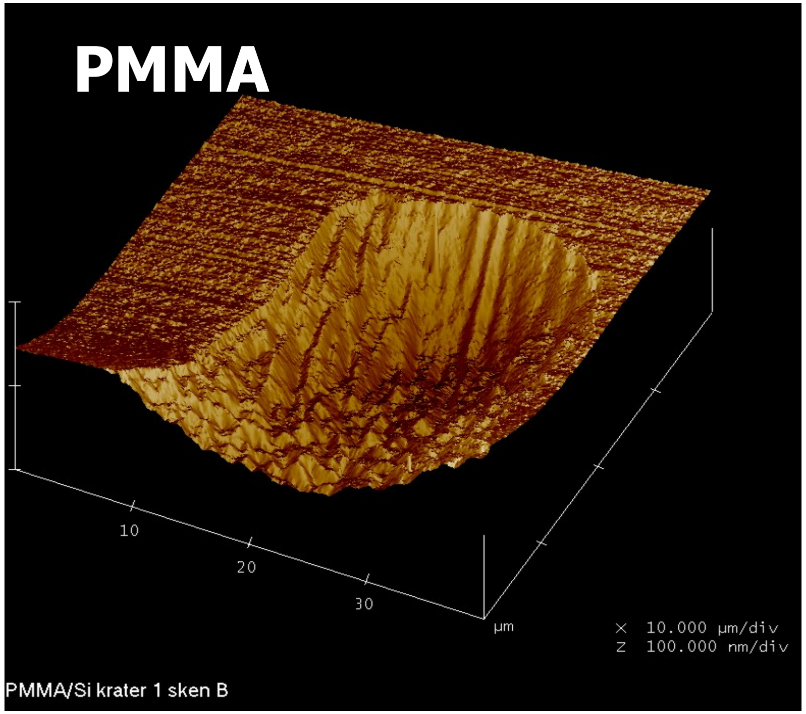
Pictures made in the new Nanoscopy Laboratory of IP AS CR in May 2004.

PALS XUV Zn laser, single exposure 200 µJ

AFM in the tapped mode.

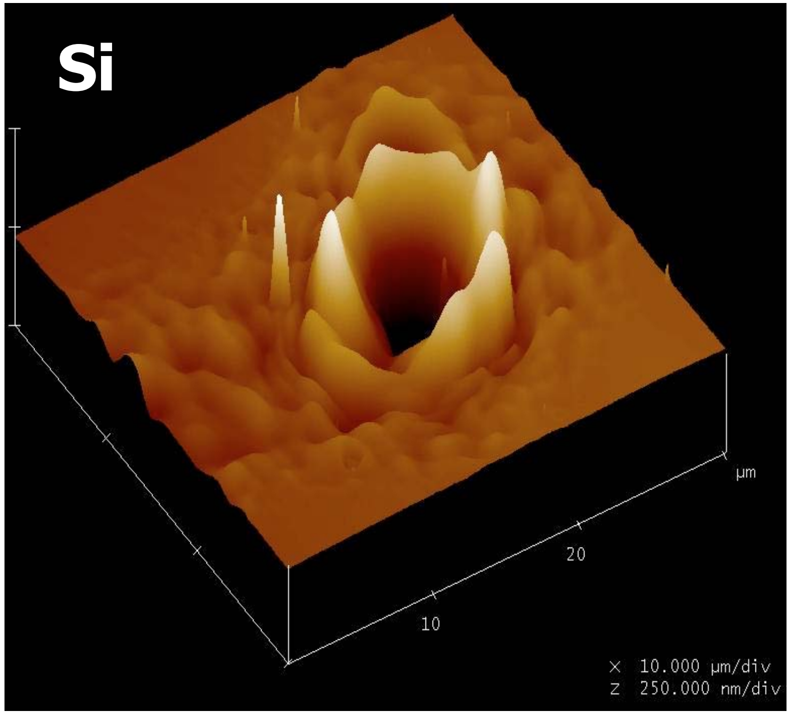
Ablation of PMMA and polycrystalline Si by soft X-ray laser

Single XRL shot, 0.4 μm Al filter
focused energy ~100 μJ



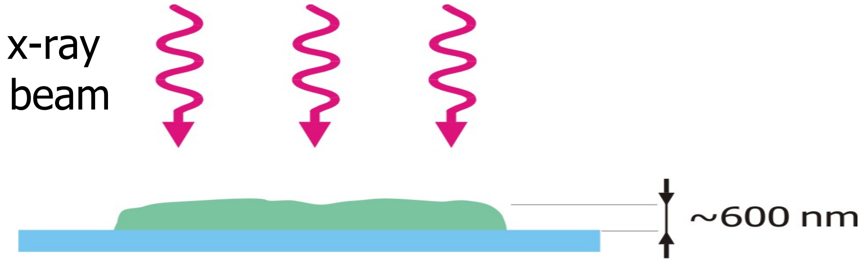
<u>Sharp edges of the crater</u>:
ablation is predominant process involved

Single XRL shot, no filter
focused energy ~200 μJ



<u>Melted structures at the crater edge</u>:
ablation <u>and</u> melting involved
(irradiance below ablation threshold)

Studies of radiation stability of DNA

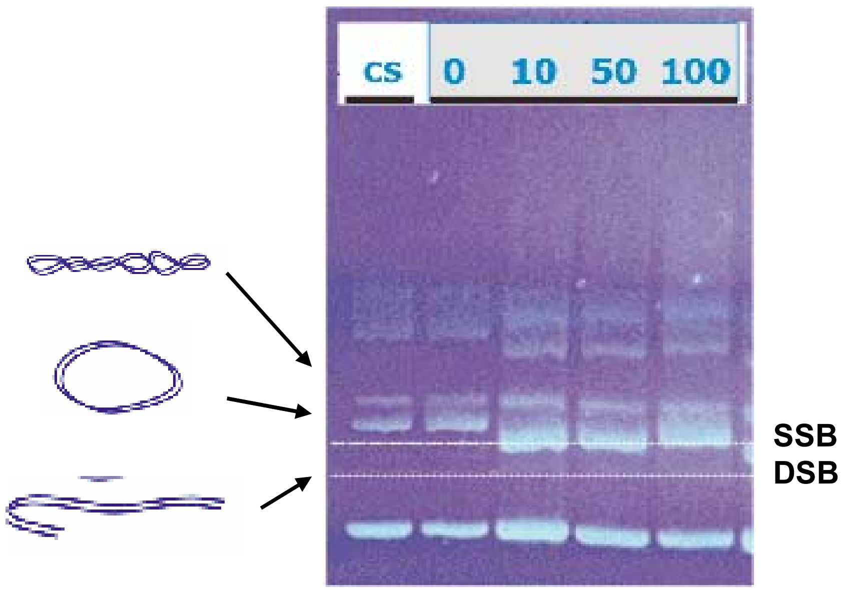


Plasmid: extrachromosomal dry
form DNA pBS 189

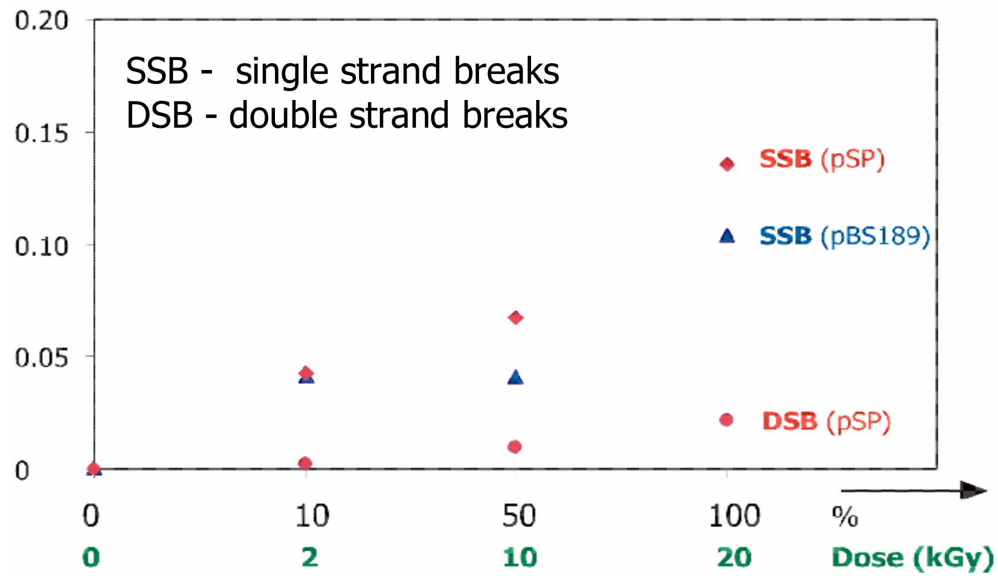
First ever DNA radiation stability tests in the soft x-ray spectral region.

Single (SSB) and Double Strand Breaks (DSB) observed at radiation doses of 10-100 kGy

Electrophoretical analysis of a of a dissolved sample



Number of breaks per plasmid



Soft X-ray Contact Microscopy (SXCM) of living micro-organisms

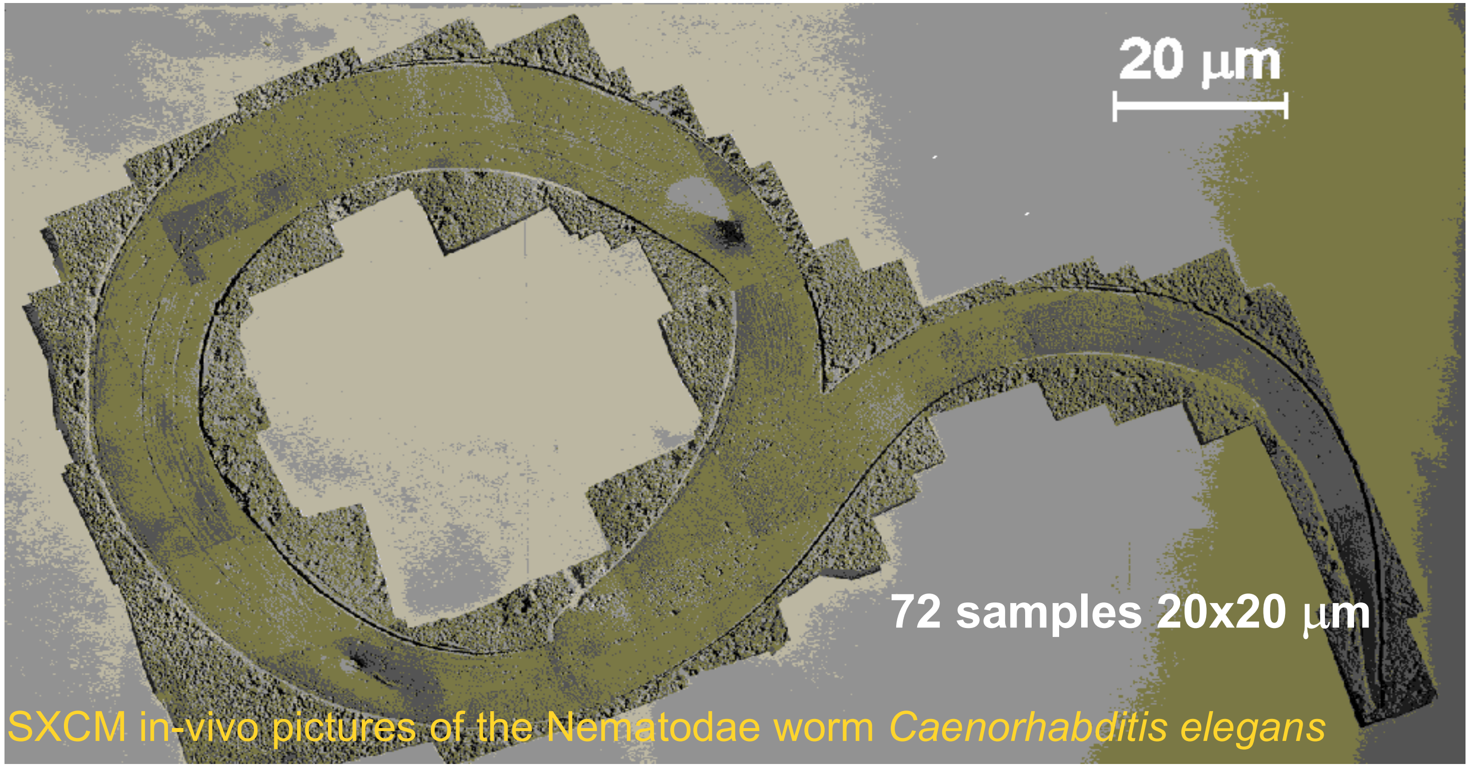
- XUV irradiation of samples + XUV spectroscopy
- developing of imprints on PMMA resists by etching
- AFM scanning of the etched relief

PALS 1ω & 3ω point focus

Au, Mo, PTFE targets

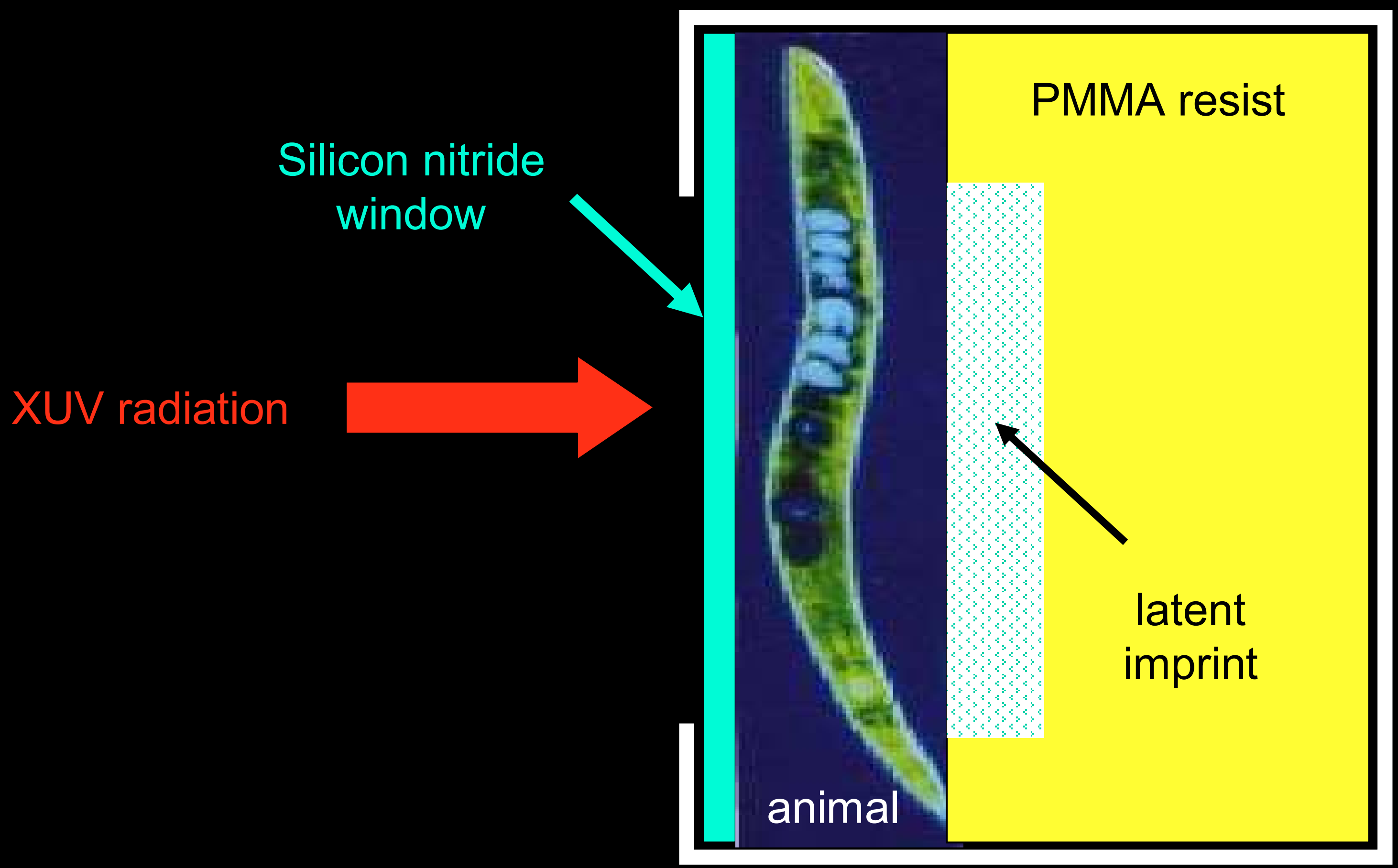
I > 10^{14} Wcm^{-2}

The first SXCM application for multicellular organisms.



SXCM in-vivo pictures of the Nematodae worm *Caenorhabditis elegans*

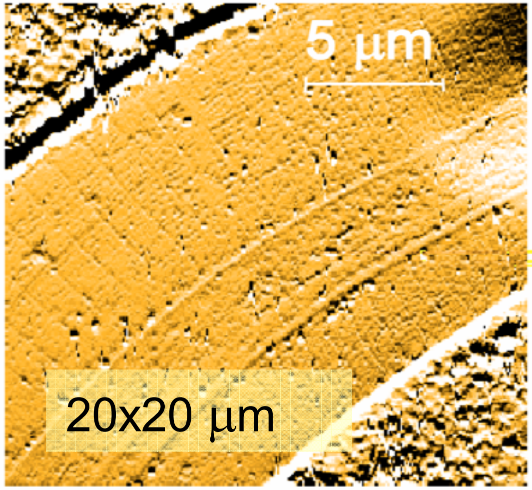
Irradiation cell for SXCM



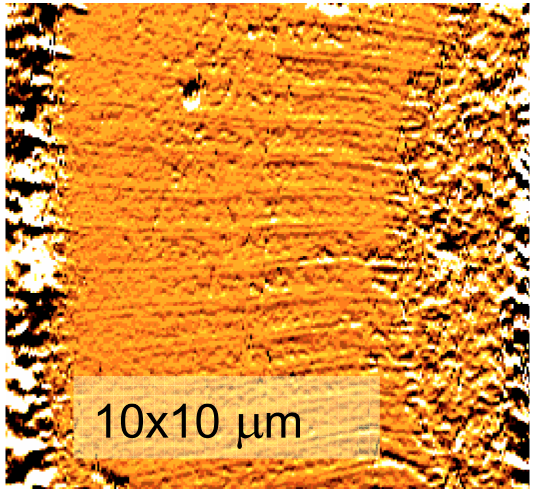
Details of C. Elegans internal structures

SPIE 48th Annual Meeting
San Diego, Proc. Vol. 5196;

Laser & Particle Beams

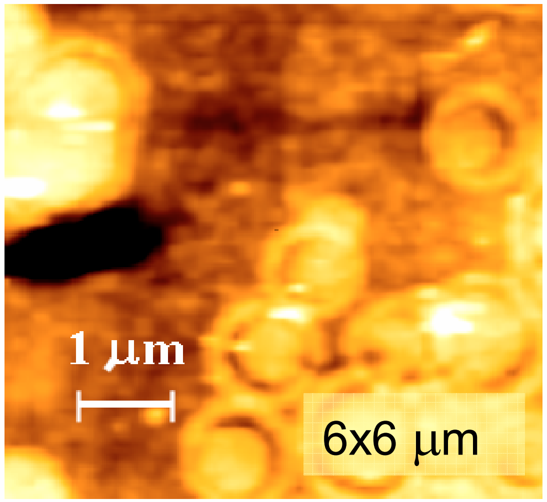


Cuticle with annuli

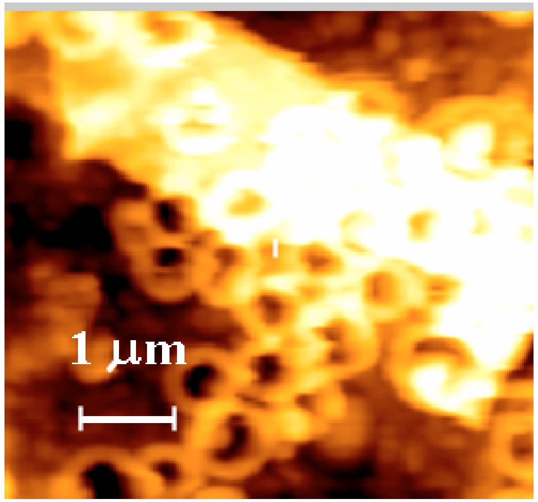


Muscle fibers

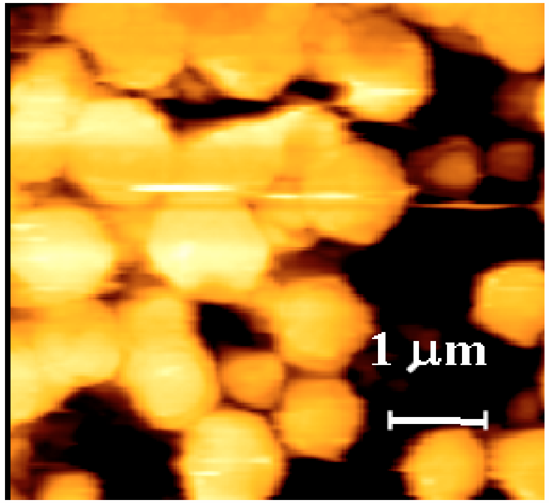
Cell nuclei:



hypodermal nuclei



neuronal nuclei



muscle nuclei

OPTIMISATION OF LASER ION SOURCES

Generation of fast highly-stripped ions in solid-target plasmas

at various
- target material (Al, Cu, Mo, Ag, Ta, Au)
- beam energies (80-750 J)
- beam colours (1ω - 3 ω)
- beam incidence angles
- focus position (FP) => focal spot size)

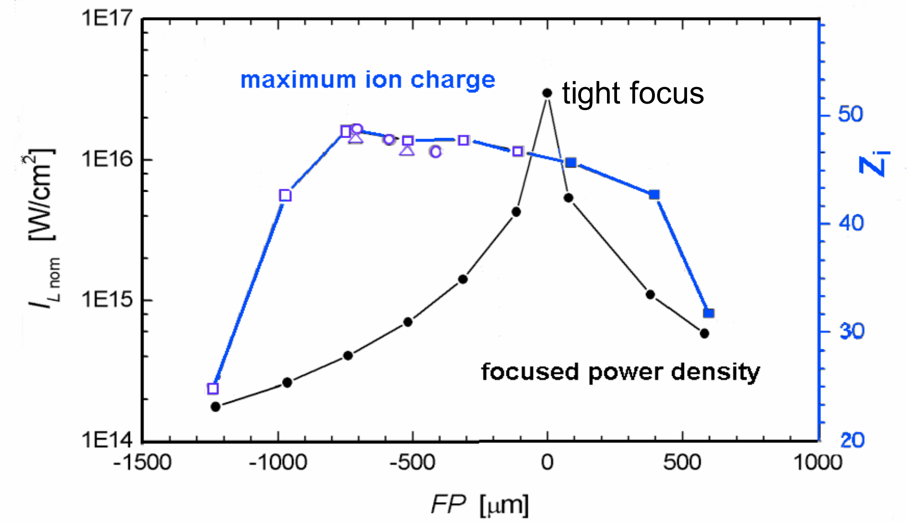
In parallel: Ion implantation experiments

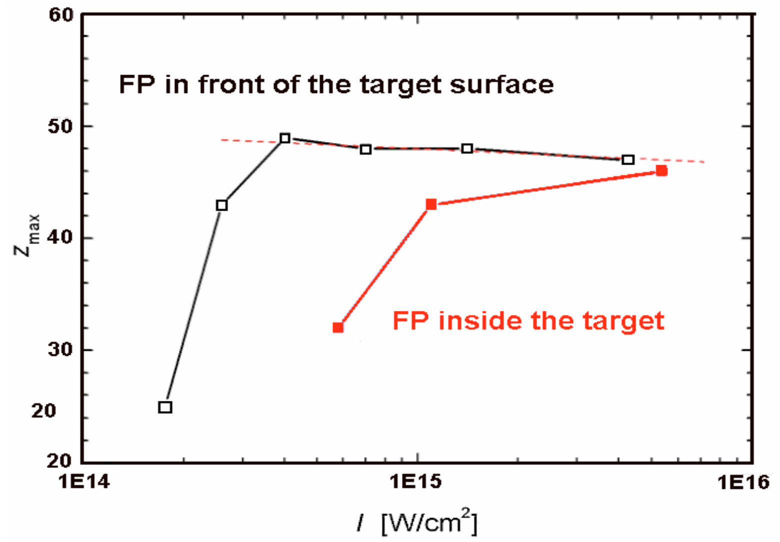
- implanted ions: Cu, Ag, Ta
- samples: PET, PEEK, kapton, C, Al, Si, Ti
- Rutherford backscattering analysis of implanted samples

Participating Institutions:

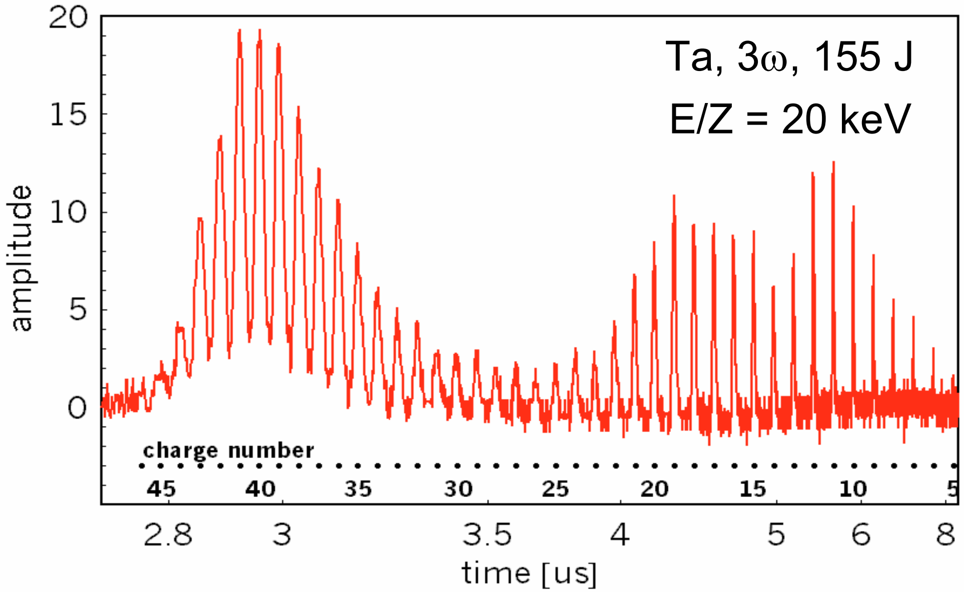
IPPLM Warsaw, IPJ Swierk, INFN Catania, Universita di Messina, INP Rez, Light Ion Technologies Bad Abbach, PALS

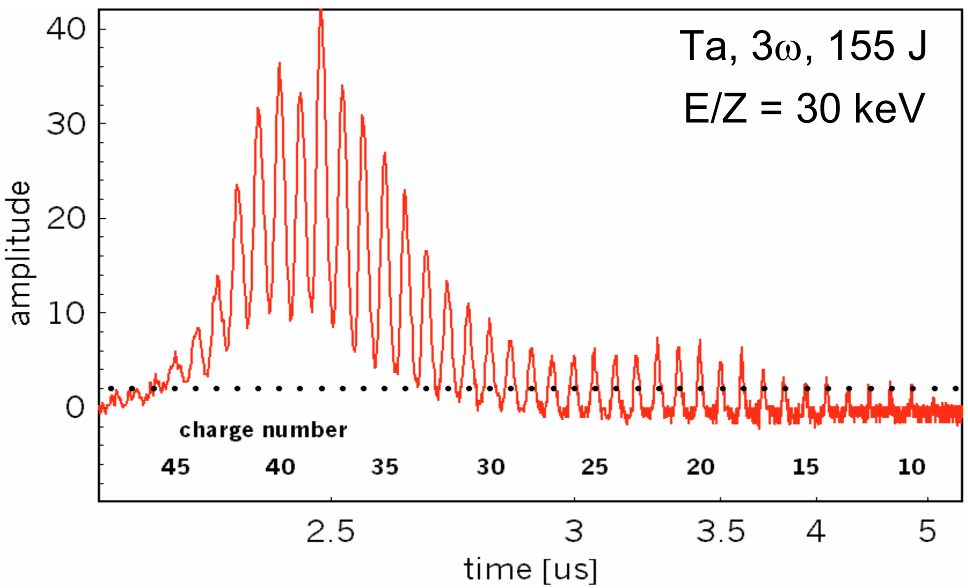
Optimum focal point position for ion generation: FP = – (250-750) μm





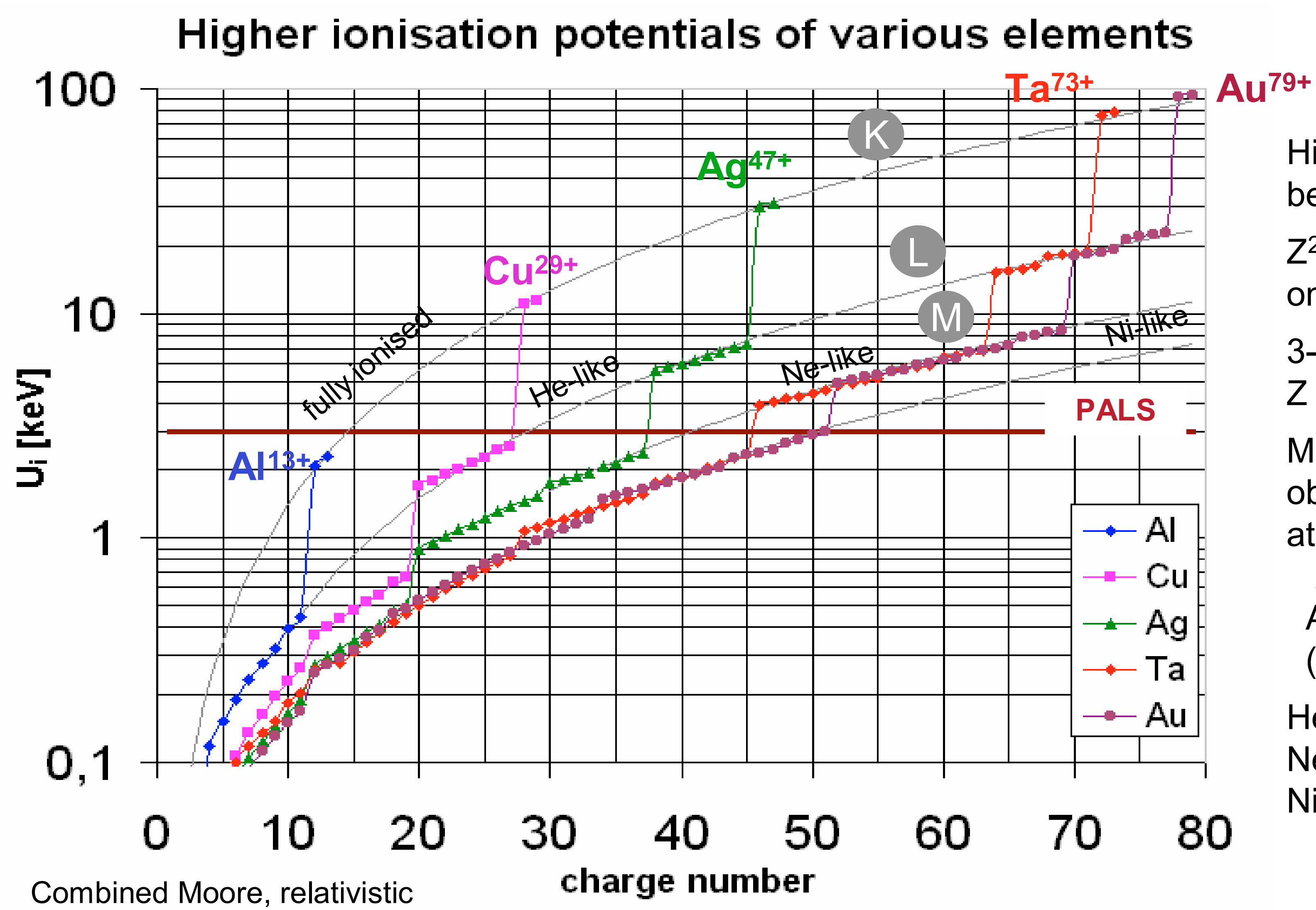
Ta ion charge spectra from EIA





Main results in general

- Several distinct groups of ions (by energy), evidently created by different mechanism and coming from different parts of the laser produced plasma.
- High energy abundant group of ~ MeV ions carries ~ 30 % of the energy in ions.
- Ultrahigh energy ions (> 22 MeV), not seen in the EIA spectra, are witnessed by nuclear track detectors.
- Ion yield strongly depends on the laser beam focusation geometry - maximum at a slightly defocused beam (FP -0.2 mm).
- The maximum ion charge approaches Z=50+ for Ta or Au ions.
- High-energy ion fluxes, inhomogeneous (partially directional), ion current densities > 1 mA/cm^{-2} (at a distance of 1 m)
- Efficient implantation of ions has been demonstrated, in up to depths of several hundred nm in metals, and several μm in plastics.



High energy jumps between e-shells

Z^2 dependence within one shell

3-5 keV needed for Z > 50+

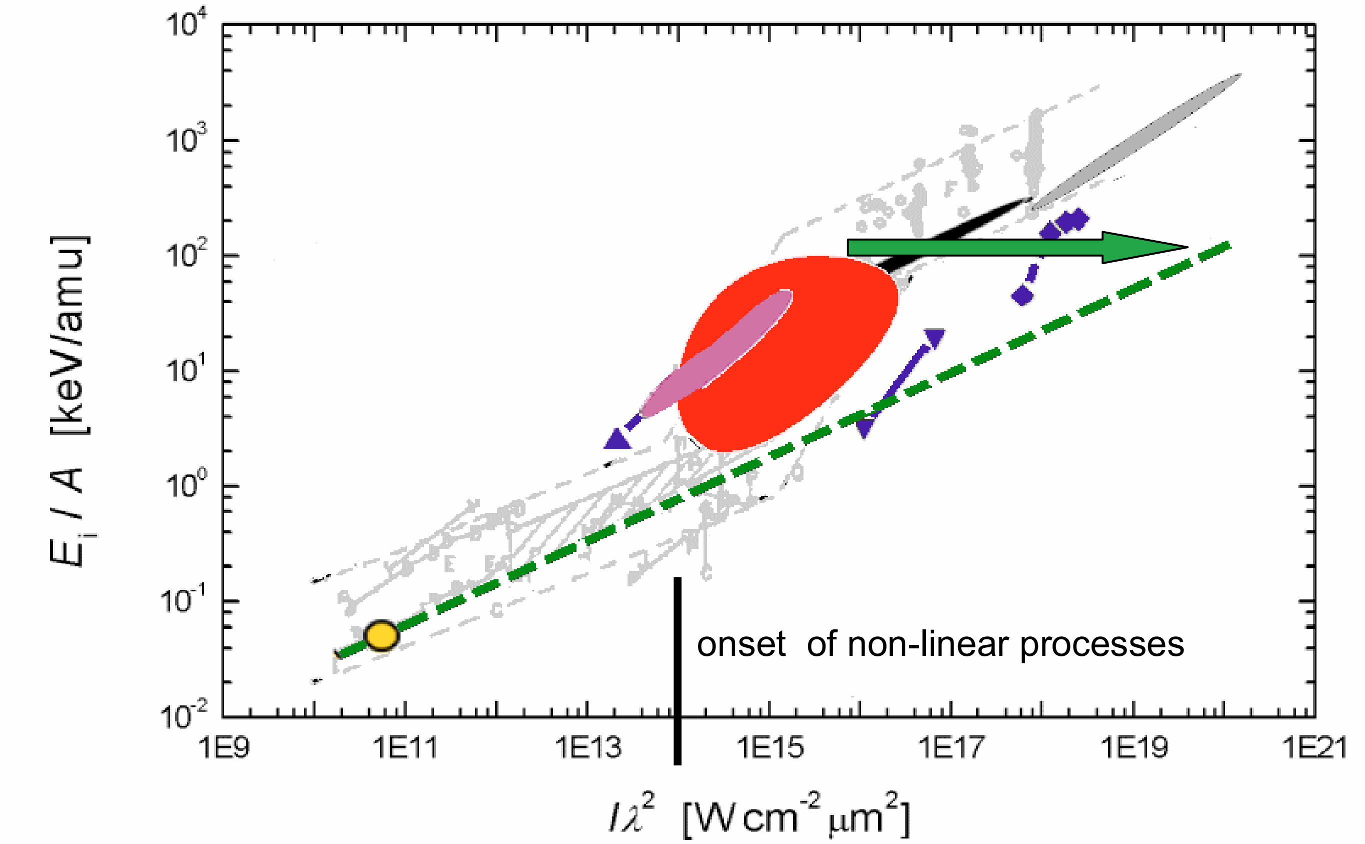
Maximum ion charge observed at PALS:
Al 13+, Cu 27+
Ag 36+, Ta 49+,
(Au > 50+)

He-like ions : A<31
Ne- like ions: A<51
Ni-like ions : A<79

Combined Moore, relativistic Hartree Slater and Hartree Fock calculations by J. Scofield, LLNL

=> High-Z ions originate in localised hot-spots, produced by non-linear processes (beam filamentation & self focusation). Just ions accelerated in local virtual cathodes to high energies escape recombination.

Maximum ion energies E_i/A at various laser power densities



Long- pulse lasers (Gitomer 1986)

ps-lasers (Clark 2000)

sub-ns, ps & fs lasers (Zhidkov 1999, Badziak 2003)

PERUN sub-ns laser (Laska 1996, 2002)

PALS sub-ns TW laser (2001-2003)

low-power ns-laser Catania (Laska 2002)

Ion energy scaling if non-linear effects are negligible

Increase in effective power density due to non-linear processes (e.g. laser beam self-focusing)

Laser-induced shock waves

- **Studies of equations of states of C and Fe at Mbar pressures**
- **Smoothing effects of foam layers**
- **Phase transitions at very high pressures**

Collaboration with Universita degli studi di Milano-Bicocca, 2002-2004 (D. Batani et al.)

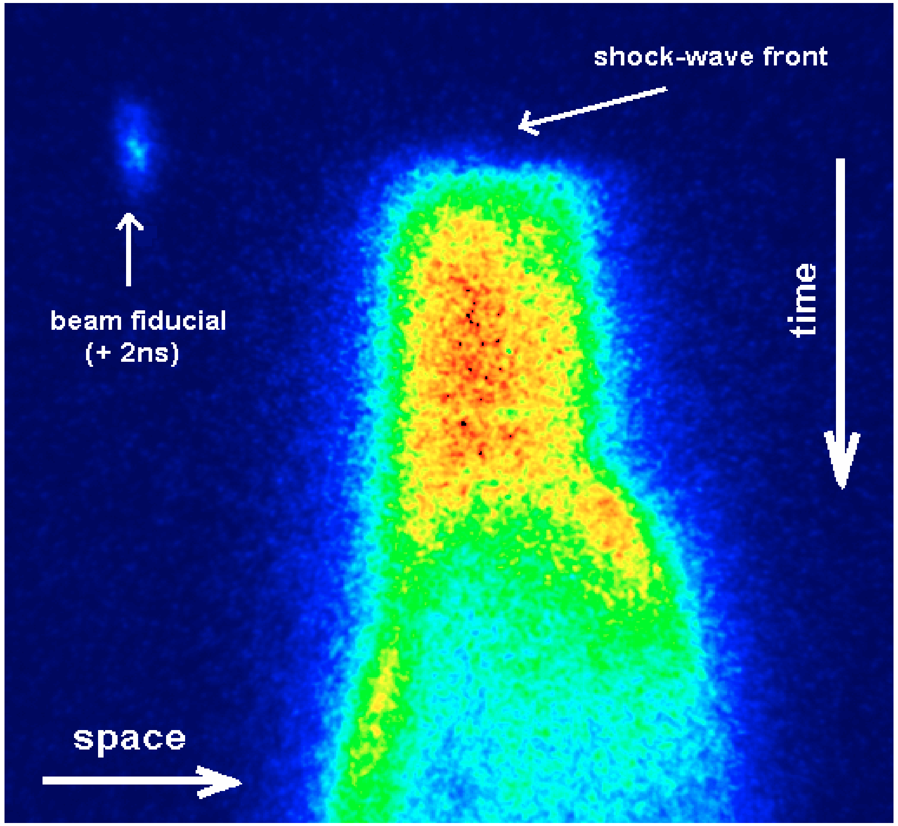
Stepped and layered targets (Al-Al, Al-C, Al-Fe, CH-C-foam)

Time-resolved (streak-camera) imaging of the self-emissivity of the target rear.

=> Shock wave velocity
=> Shock pressure (Hugoniot data)

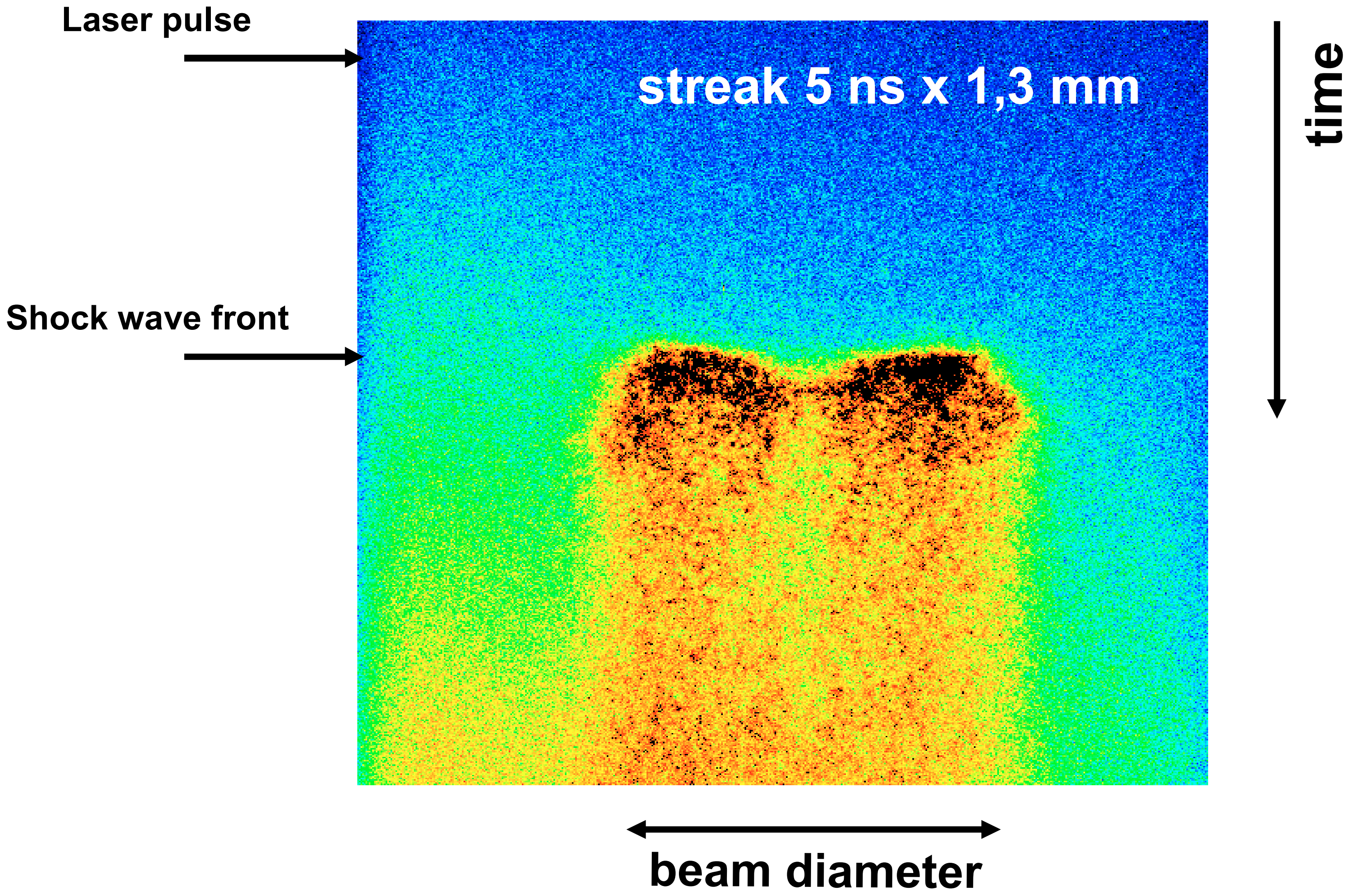
Shock (ablation) pressures up to tens of Mbar can be reached at PALS.

Streak-camera image showing shock wave structure in the layered target
picture scale 1.3 mm x 5 ns

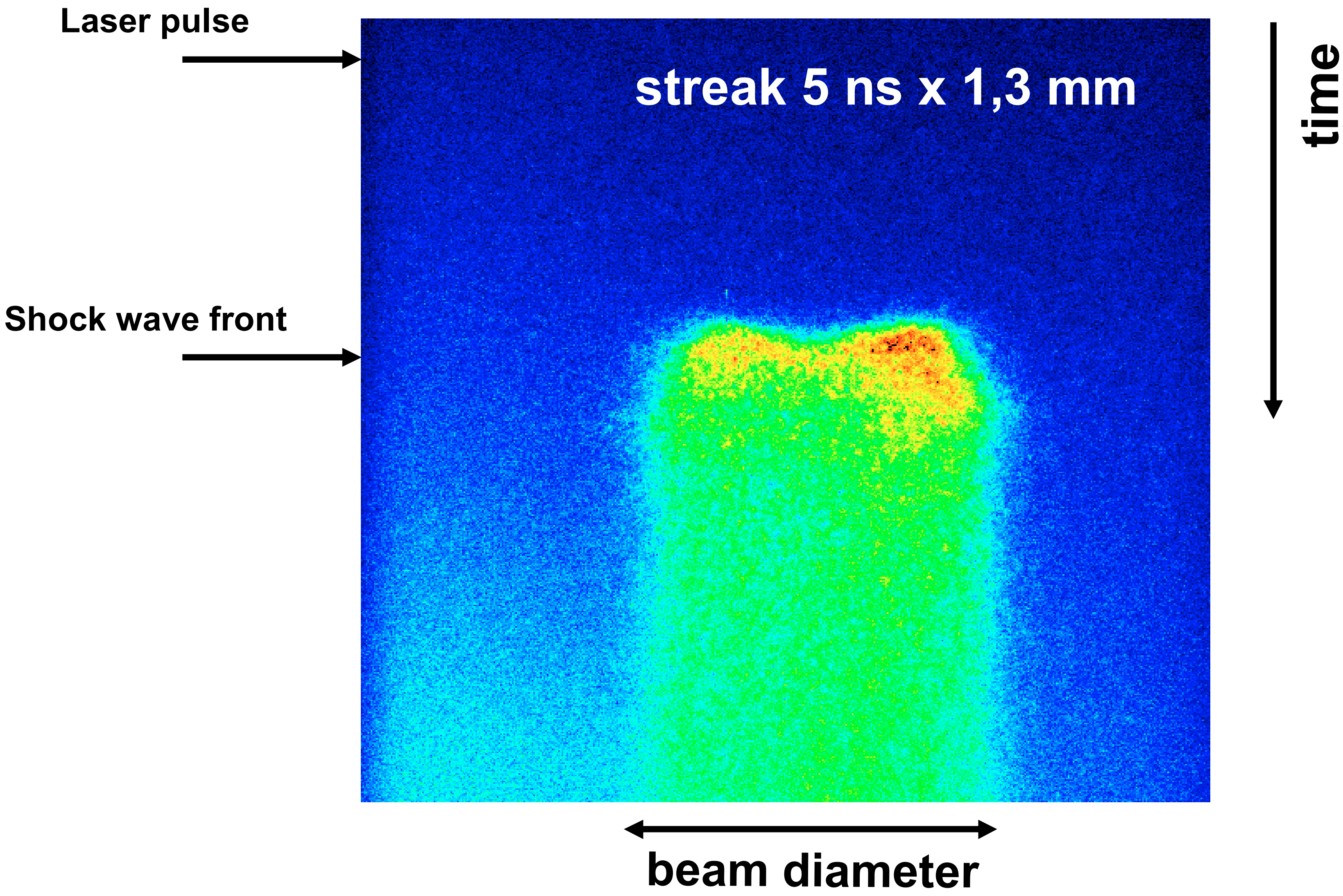


Infrared streak camera Hamamatsu C5680

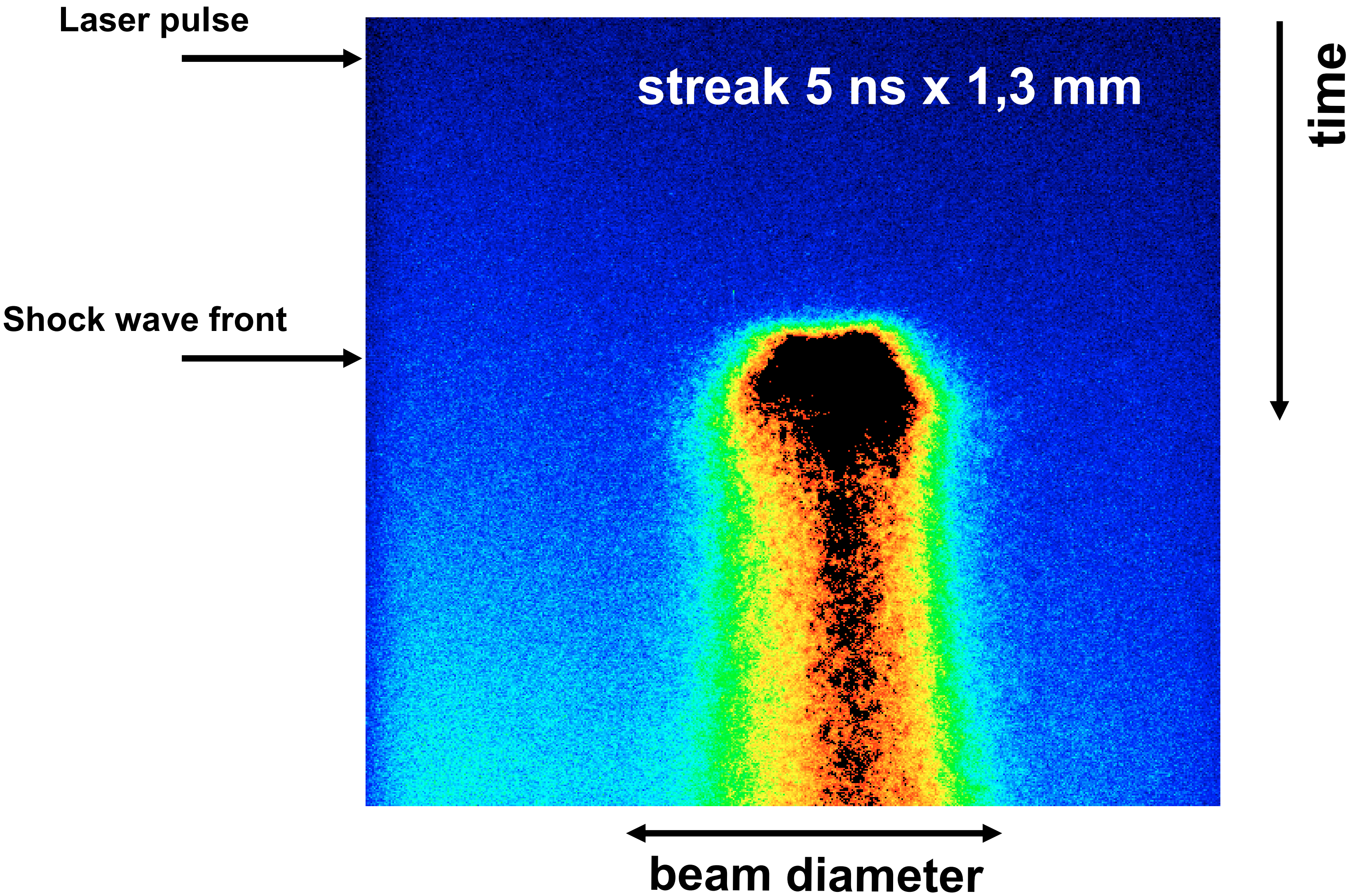
Shock Wave Studies
June 2004



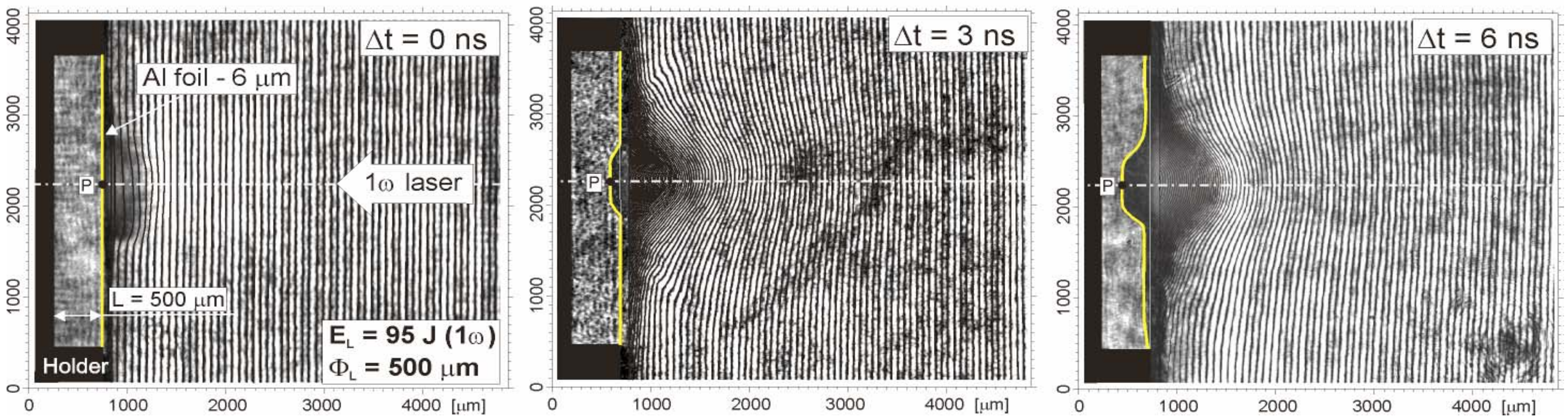
Shock Wave Studies
June 2004



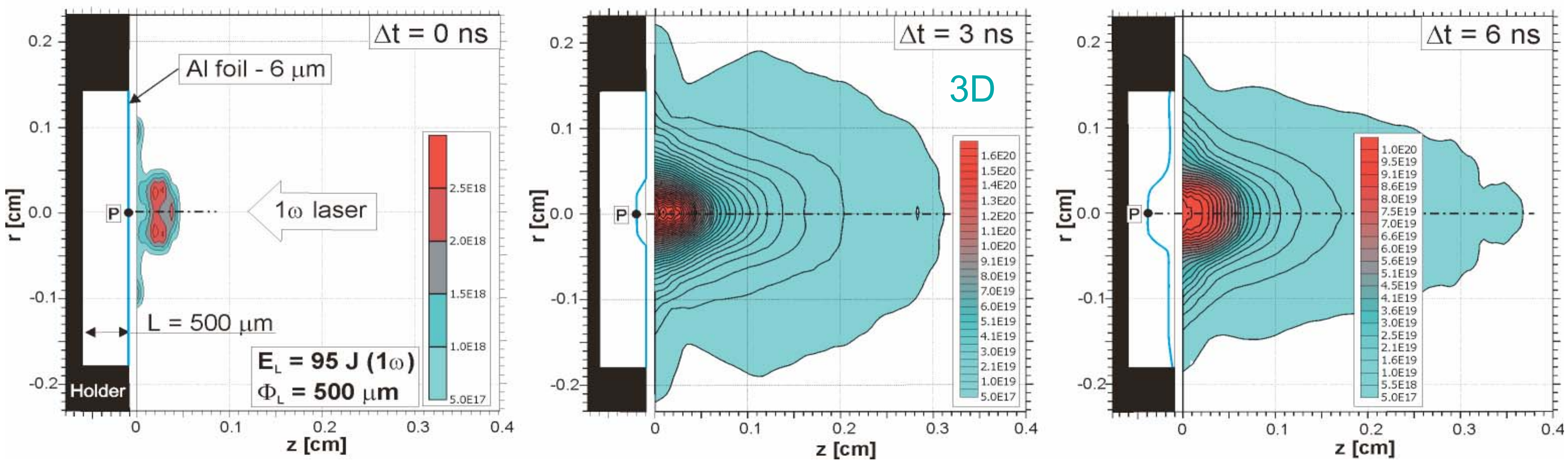
Shock Wave Studies
June 2004



Foil acceleration I



Time sequence of interferograms/shadowgrams of the accelerated Al foil



The processed densitograms/contourgrams (T. Pisarczyk, IPPLM Warsaw)

The foil velocity at the central point P: $3.5\cdot10^{6}$ cm/s $6.2\cdot10^{6}$ cm/s

PALS – Fusion related

”Keep in Touch Activities”

Current issues:

Laser imprint smoothing in voluminous absorbers of low-density porous matter (foam targets)

In colaboration with IPPLM Warsaw (2002-2003)
Co-ordinators: J. Limpouch, T. Pisarczyk

Laser imprint smoothing in a plasma absorption layer produced by a laser prepulse

Current domestic experimental project
Co-ordinator: K. Mašek

Theoretical studies of electron and ion acceleration in crossed laser beams

Base for a new experimental project
Co-ordinator: V. Petržílka

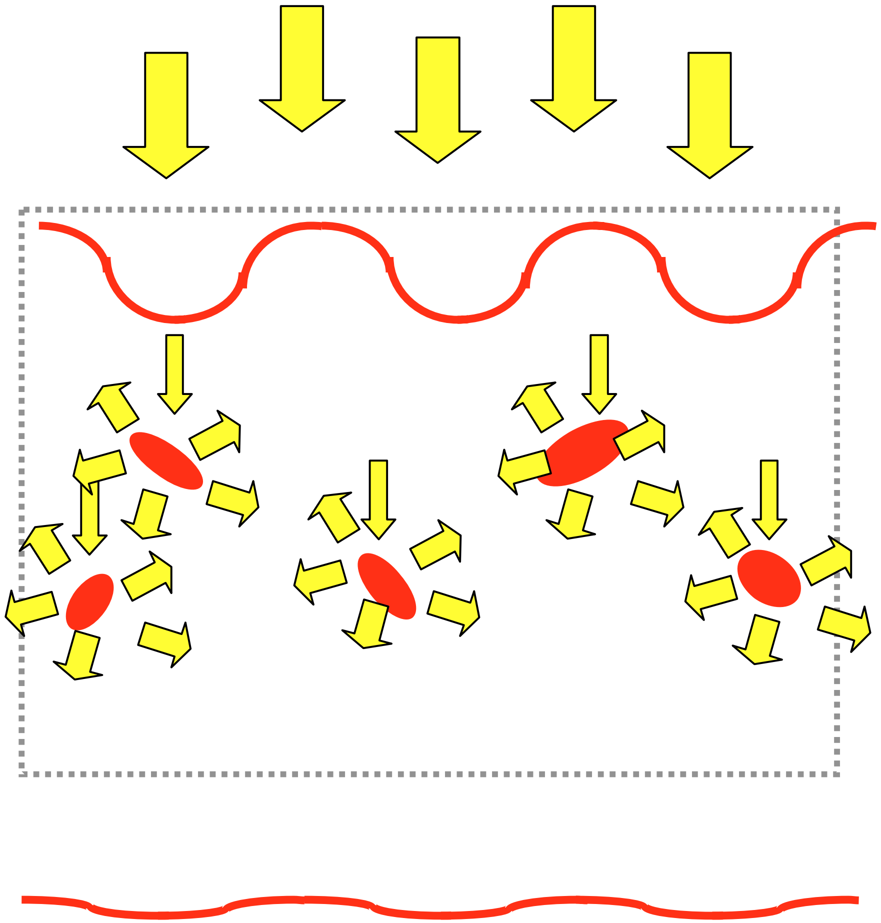
IPP Laser Plasma Department

main operator of the PALS Research Centre

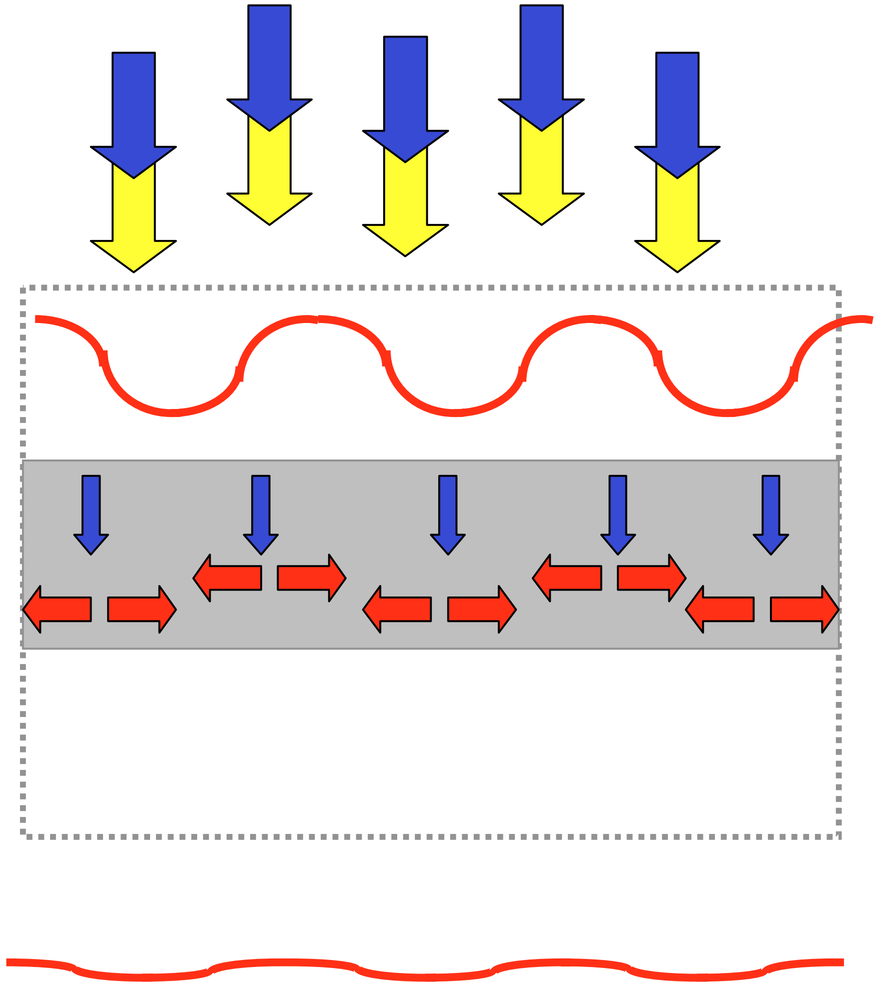
key facility: The Prague Asterix Laser System

Laser imprint smoothing

In a porous material (foam):



In a prepulse-produced plasma:



Thermal smoothing by a double laser pulse

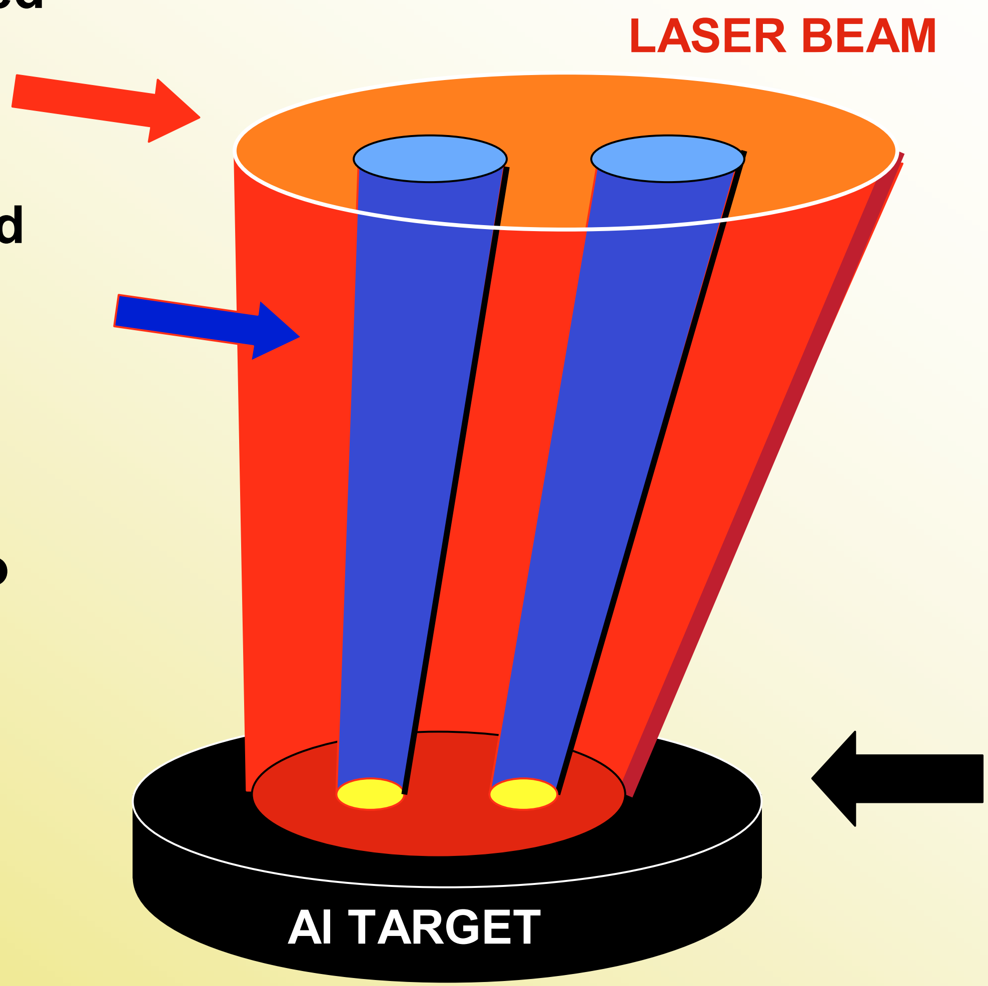
K. Mašek, E. Krouský et al.

**Pre-plasma produced by a defocused infrared beam
(focal spot diameter 0.3 mm)**

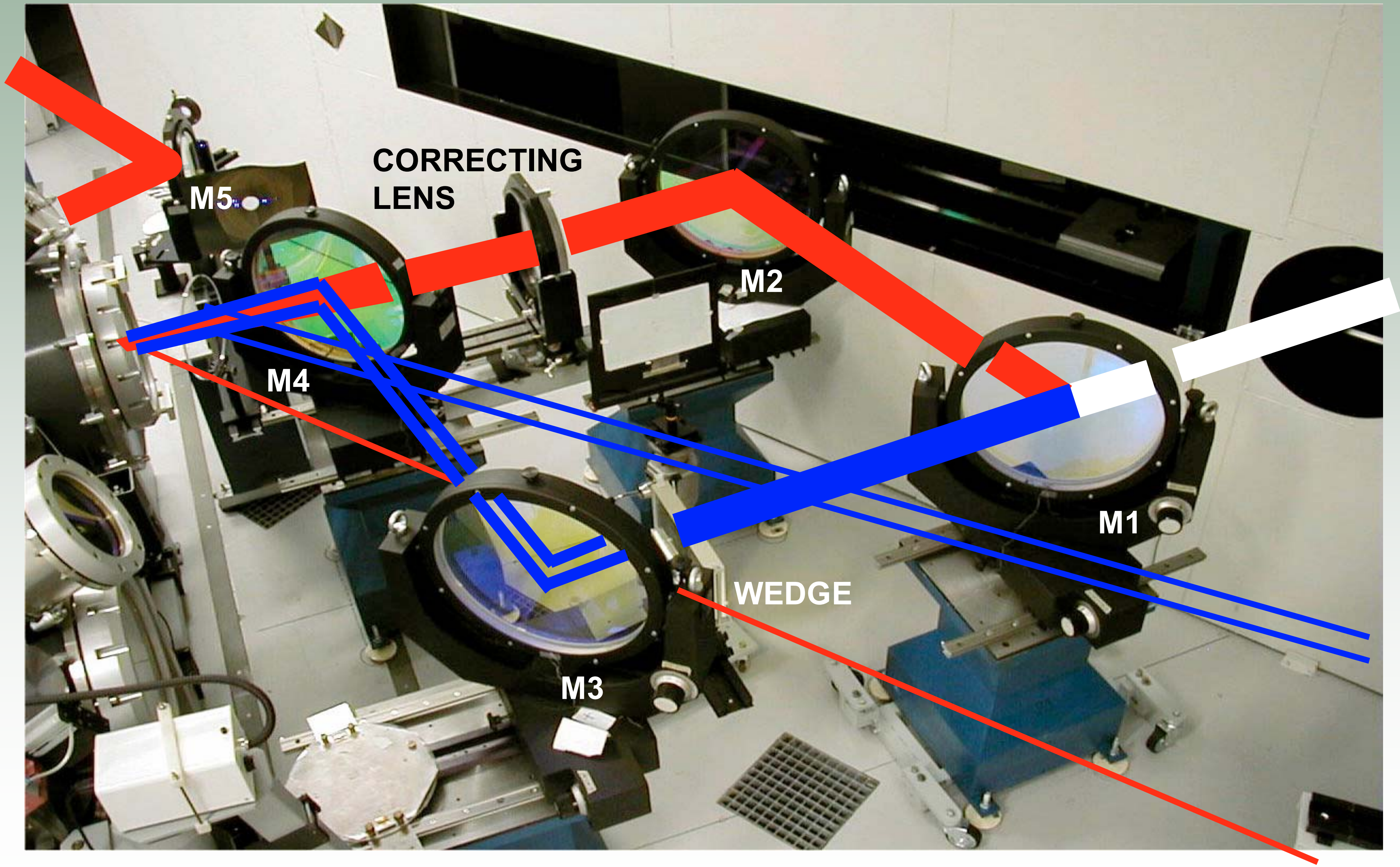
**Two hot spots generated by focused blue beams delayed by 0.5 ns.
Distance of the spots 0.2 mm.**

Plasma expansion is studied by two X-ray pinhole CCD cameras.

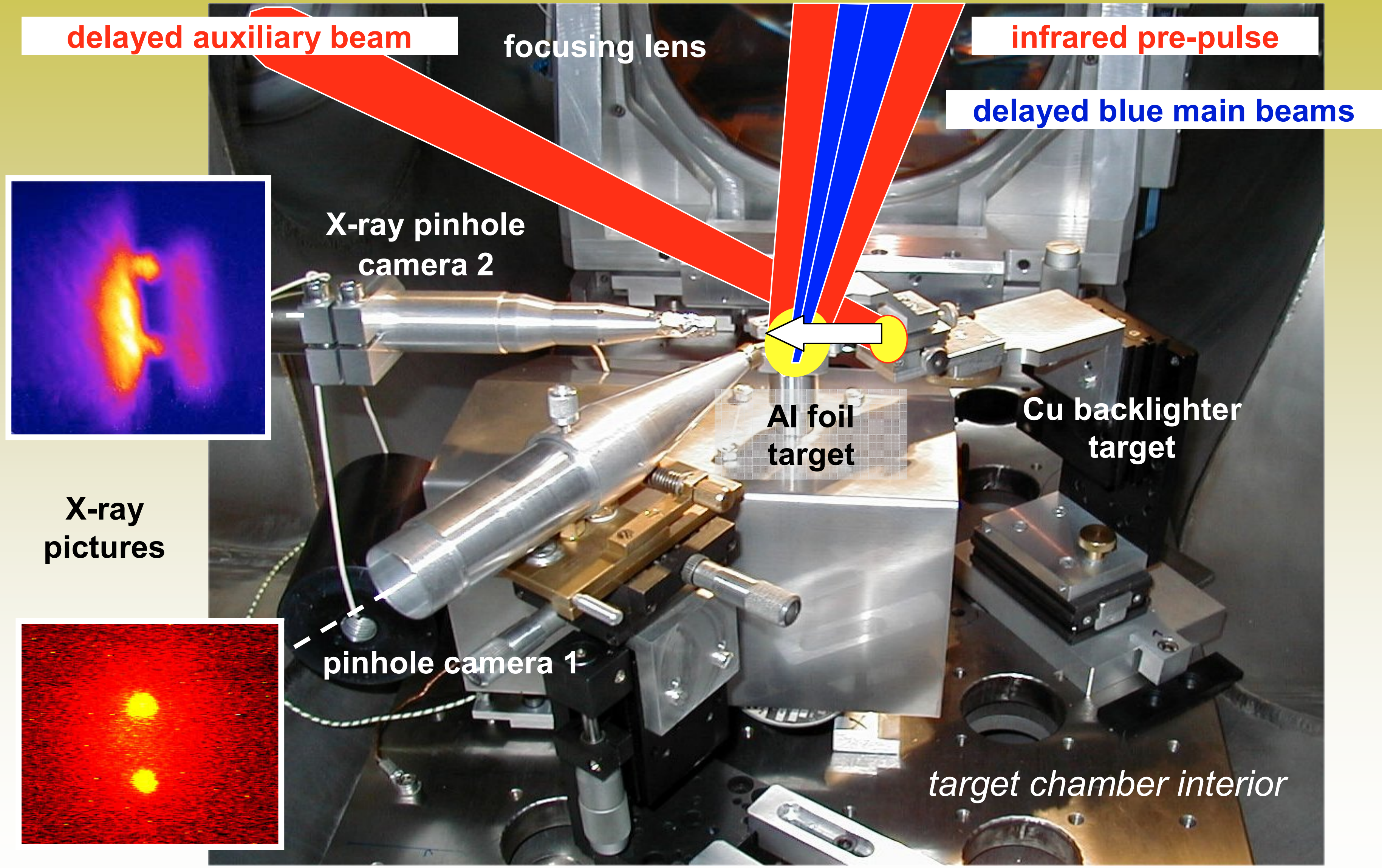
X-ray backlighting provides shadowgrams of the dense plasma regions.



Laser beam lines in the double pulse arrangement

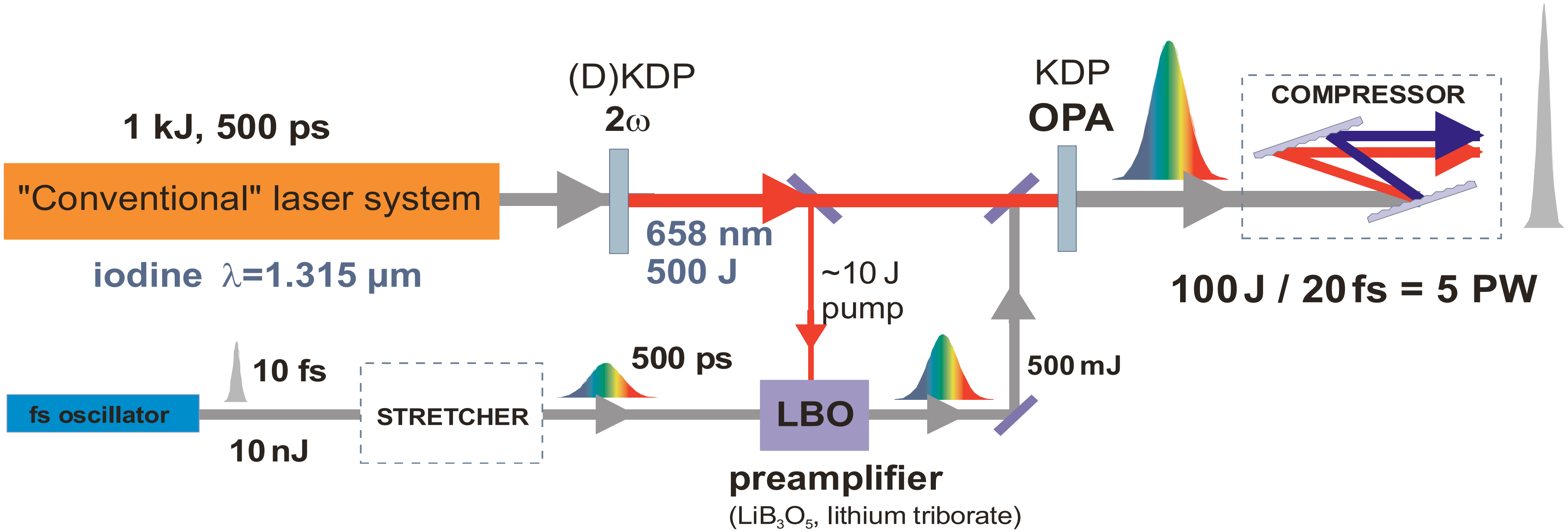


Targets and diagnostics

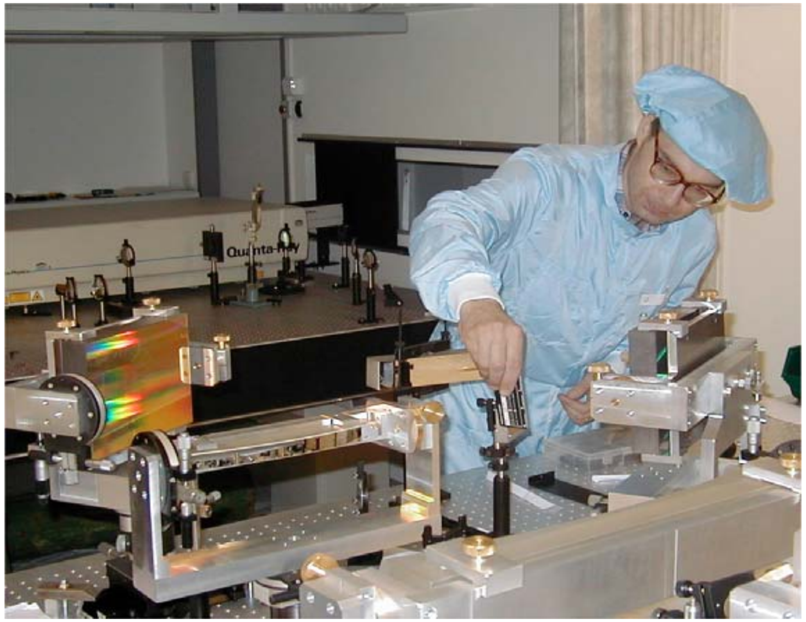


Second round of experiments just under way

A road towards a ultra intense multi petawatt pulse:
Futuristic vision of a full scale implementation of OPCPA on PALS
Calculations I. N. Ross, P. Matousek (RAL), B. Rus (Prague)



So far: a pilot laboratory SOFIA hybrid laser system: solid state tunable oscillator in combination with iodine amplifiers will drive a small scale OPCPA chain (two distinct upgrades)



SOFIA & OPCPA PILOT EXPERIMENT

SOFIA = **S**olid-state **O**scillator **F**ollowed by **I**odine **A**mplifiers

OPCPA = **O**ptical **P**arametric **C**hirped **P**ulse **A**mplification

Femtosecond source

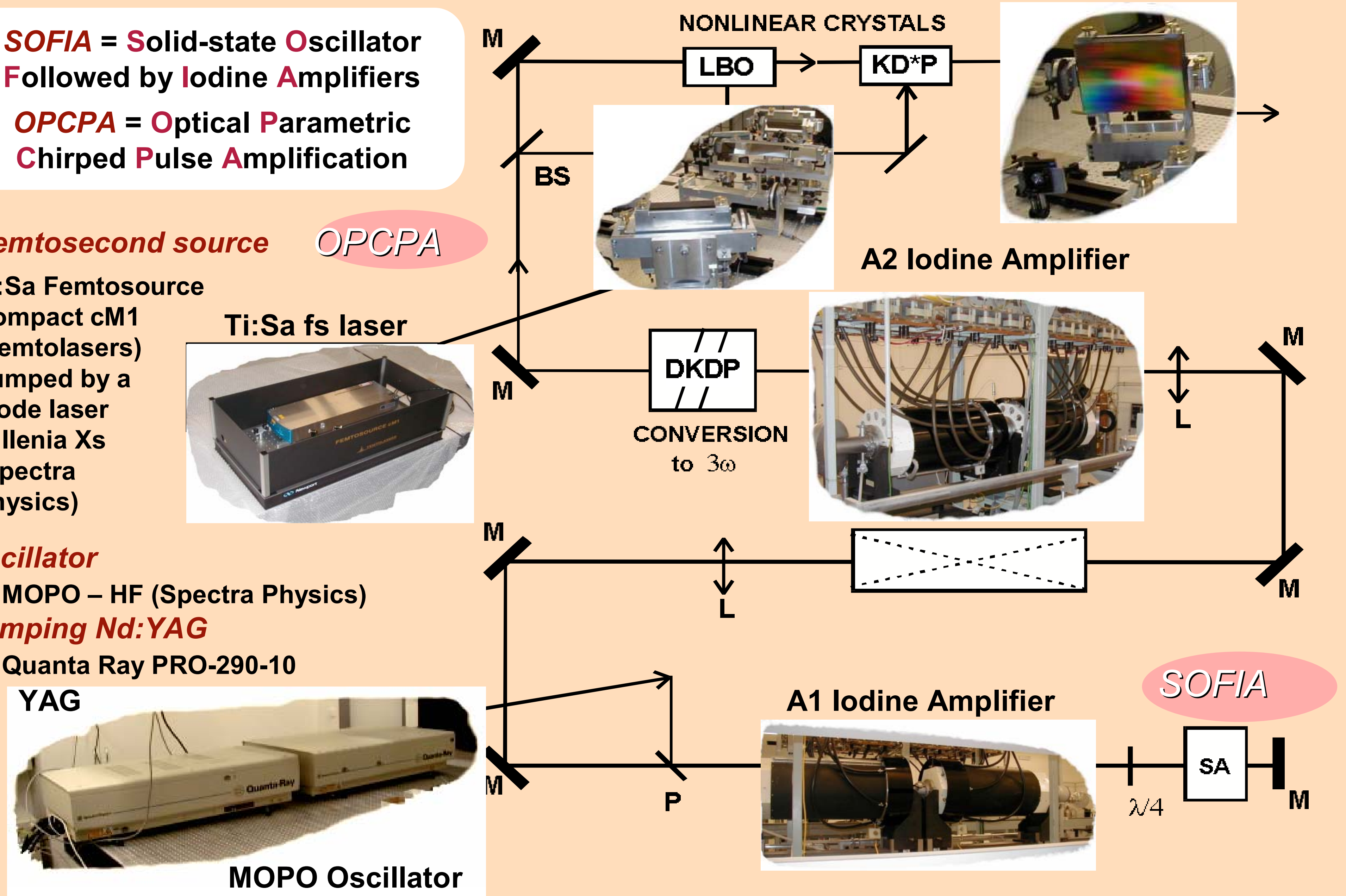
Ti:Sa Femtosource Compact cM1 (Femtolasers) pumped by a diode laser Millenia Xs (Spectra Physics)

Oscillator

MOPO – HF (Spectra Physics)

Pumping Nd:YAG

Quanta Ray PRO-290-10



PALS FUTURE

Training site for domestic and foreign students

European users laboratory incorporated into the network of large European laser research centres

Co-operation with the USA, Japan, Russia and …

Petawatt prospects: By shortening the pulse duration down to the femtosecond region (OPCPA technique) PALS has a potential to become one of the most powerful lasers in the world (OPCPA is a way to a multi petawatt)

When: ???, after a success of the SOFIA project and a good luck with a much more investment money