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Coherent soft x-ray sources and applications

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Outline

1. Second generation X-ray laser demonstration

2. The path towards high energy:
   Amplification on solid target

3. The case for High Power Soft-XRL

4. Current and foreseen applications

XUV source applications are demanding

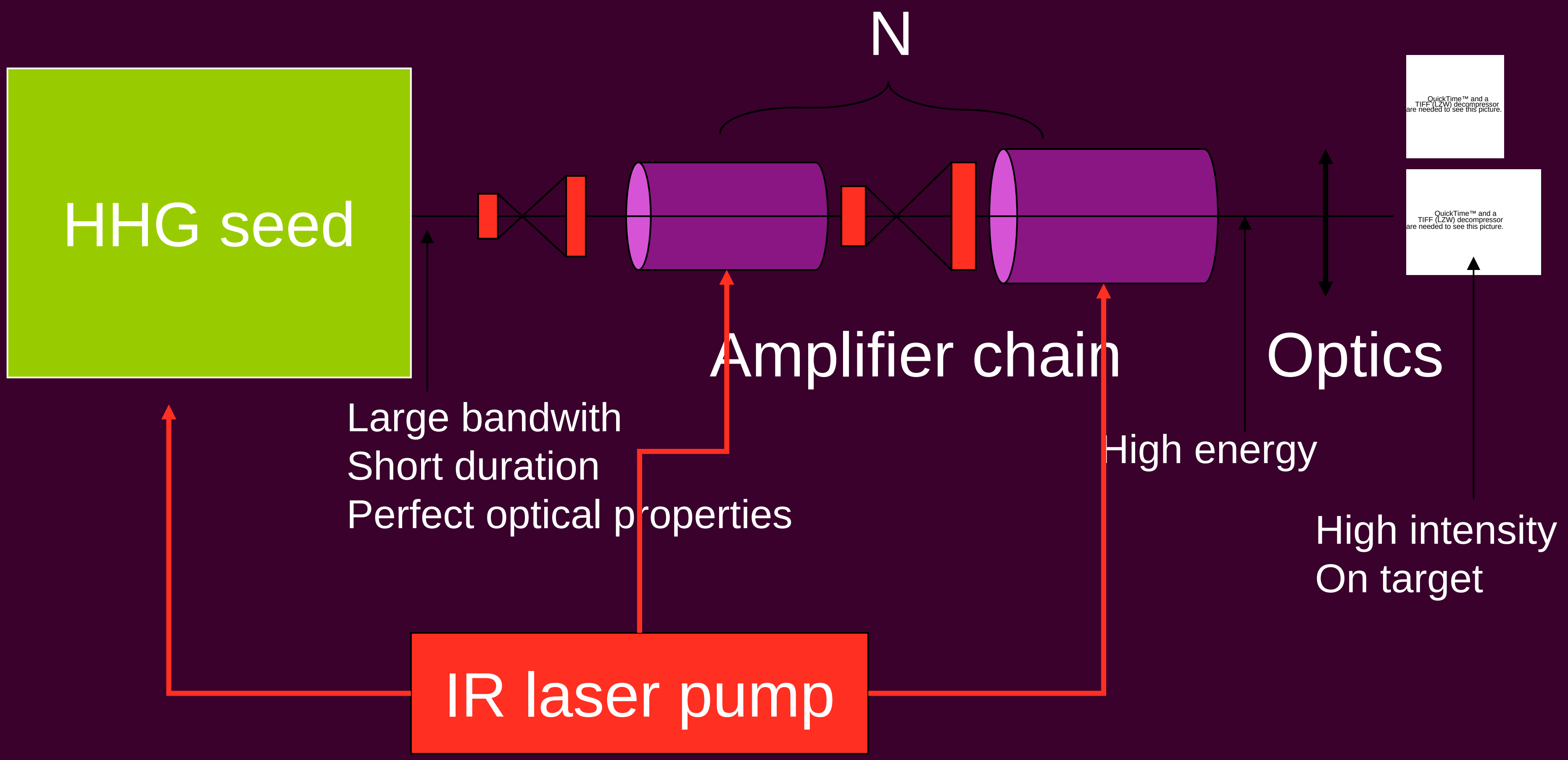
- Short pulse duration (femtosecond)
    - ⇒ Biology, pump-probe experiments, plasma physics
- Strong energy (~mJ)
    - ⇒ Biology, plasma physics, High XUV Fields
- High spatial coherence + good wavefront
    - ⇒ XUV Holography, XUV interferometry, micro-focussing
- Polarization
    - ⇒ Atomic physics, spatial filtering
- High repetition rate
- Short wavelength is often better

In 2004: State of the art for XUV sources

	X-ray laser	Harmonics	VUV-FEL
Duration	≥ 2.5 ps	< 20 fs	100 fs
Energy	≤10 mJ	< µJ	40 µJ - 1 mJ
Polarization	No	Polarized	Polarized
Spatial coherence	Weak	Full	80%
Wavefront	Depends on scheme	Good	Good
Wavelength	Water window	>10 nm tunable	30nm ->Å tunable

Injection of HHG in XRL amplifier
Second generation X-ray laser

Architecture of a 2nd Generation X-ray laser chain



Choices for the soft x-ray amplifier

SOLID TARGETS

ADVANTAGES

strong density of emitters

DISADVANTAGES

strong refraction, small gain region, evolving position

T. Ditmire et al, PRA, 1995

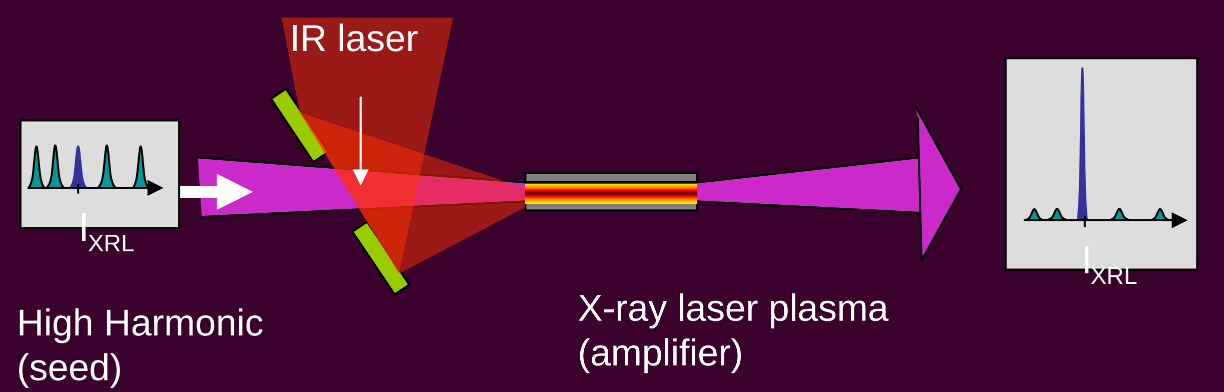
GAS TARGETS

ADVANTAGES

no refraction, known gain position, high rep rate

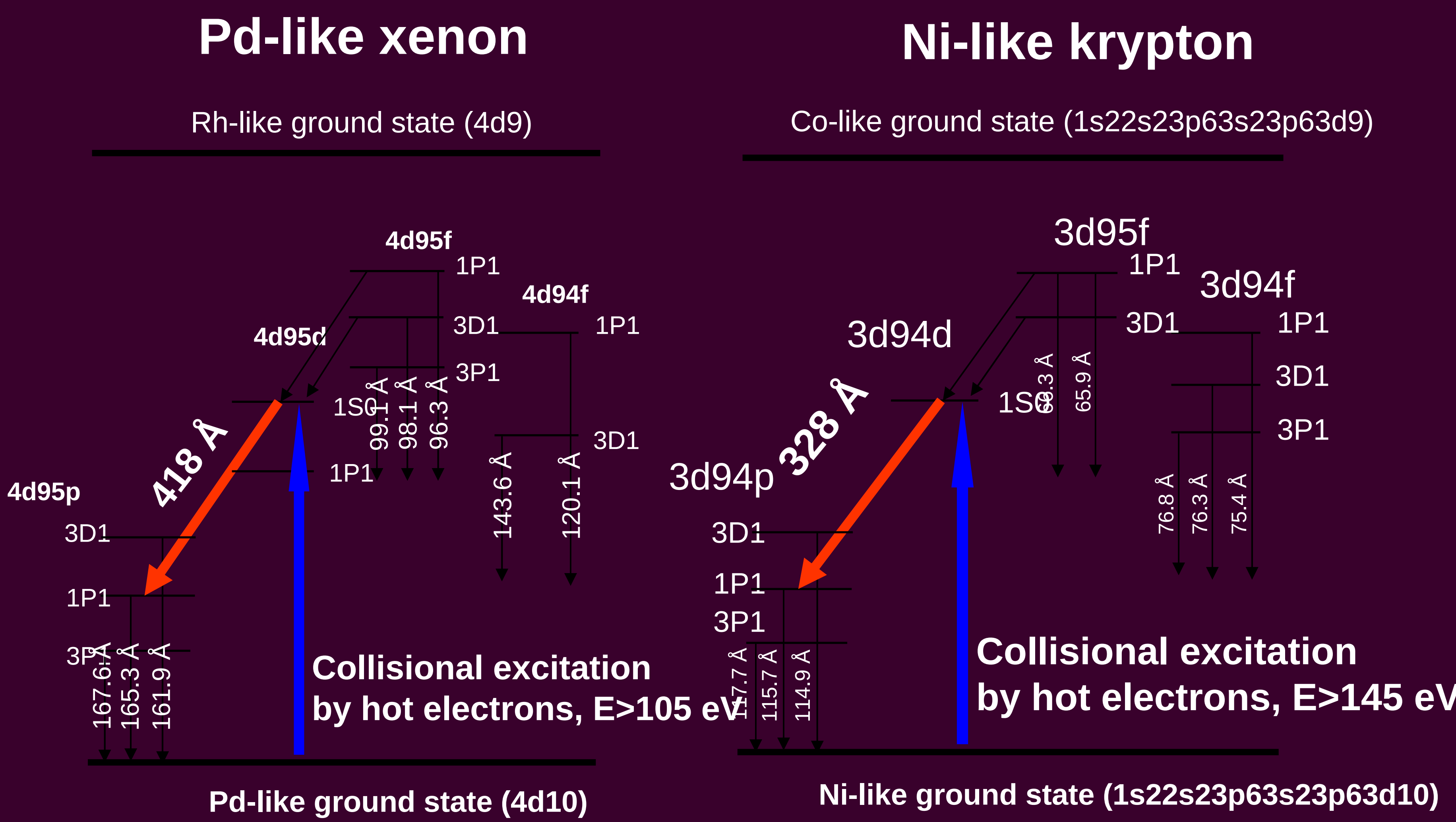
DISADVANTAGES

low emitter density

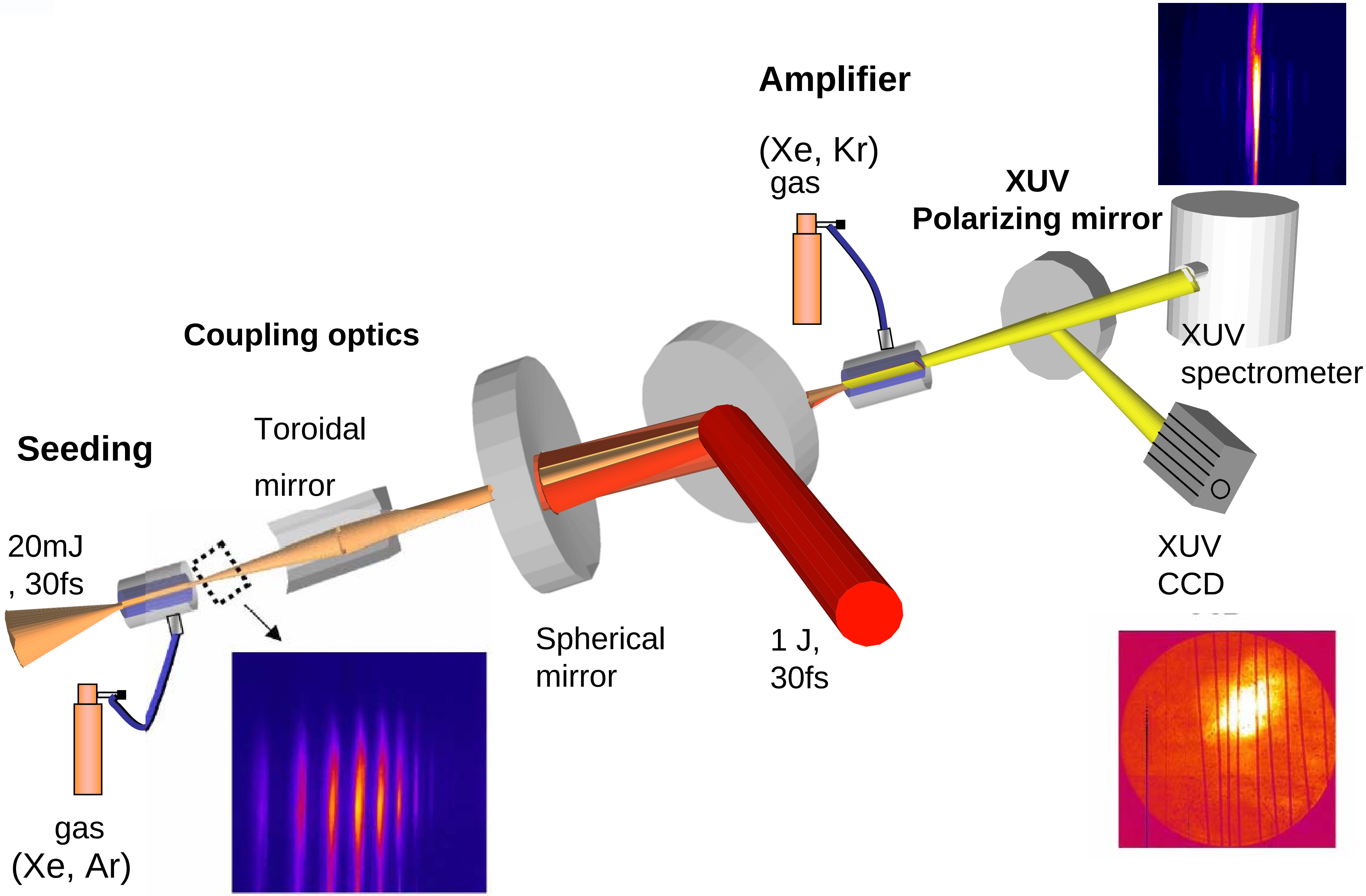


Optical field ionized X-ray laser

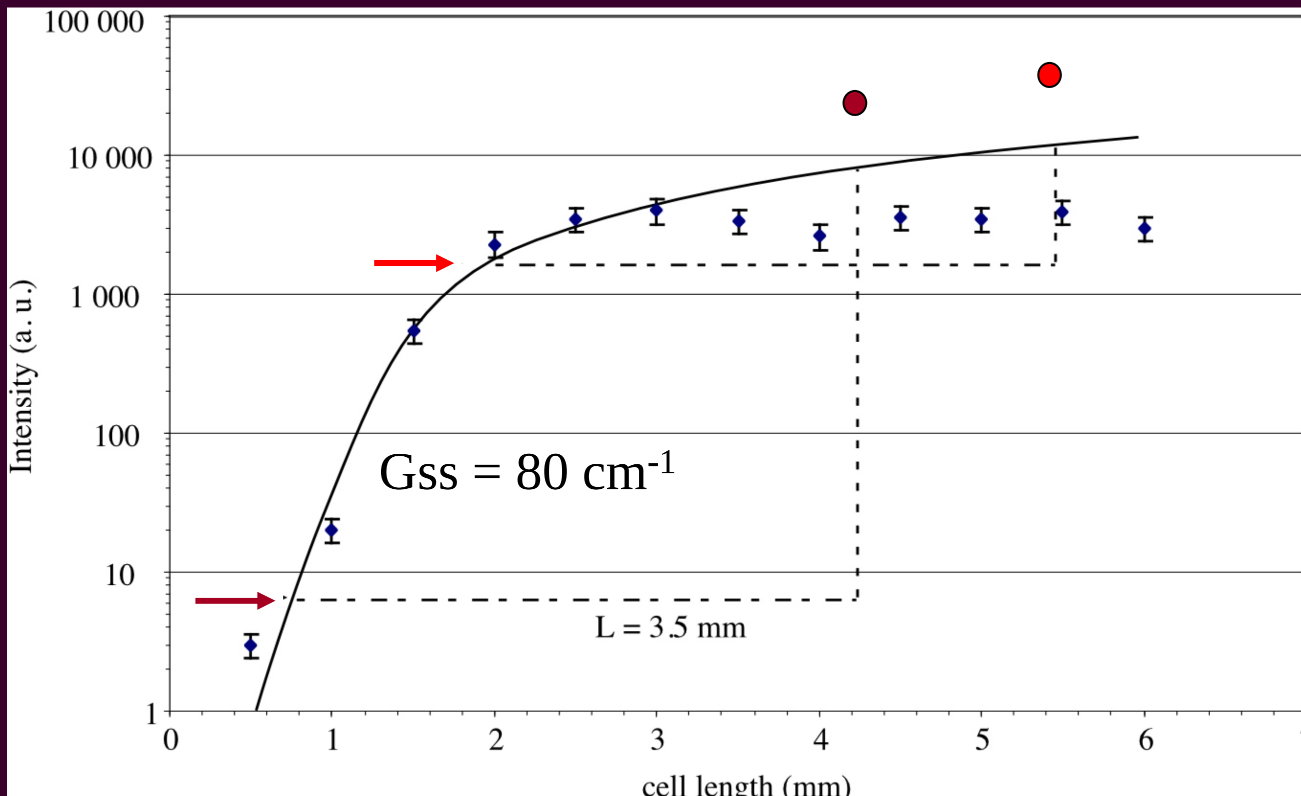
S. Sebban et al, PRL, 2002



Experimental setup



Amplification depends on the level of seeding



Level of injection

Iinj~Isat/100 : strong amplification (x200)

Iinj ~4*Isat : moderate amplification (x20)

QuickTime™ et un
décompresseur TIFF (Uncompressed)
sont requis pour visionner cette image.

Additional benefits

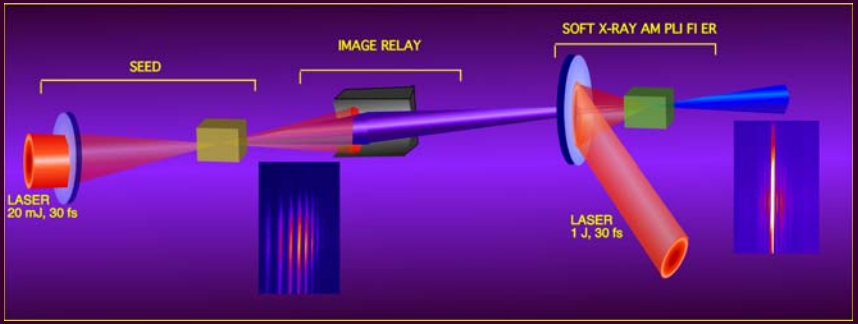
1. Improved coherence
2. Narrower divergence
3. Easy handle on polarization
4. Spatial filtering
5. Better wavefront (measured in 2nd campaign)
6. Broader Bandwidth = shorter pulse? - at least energy output indicates so

Improving the X-ray laser source

1. Higher energetic output
2. Lower wavelength
3. Shorter pulse duration (larger bandwidth)
4. Diffraction limited

Choices for the soft x-ray amplifier

GAS TARGETS



ADVANTAGES :

- Easy to set, high ampli. ×1,000
- High rep- rate (10 Hz)

DISADVANTAGES :

- Narrow spectral line ⇒ pulse ~ 1 ps
- No extrapolation to output energies above 100 µJ.
- Difficult to lase below 10 nm.

(*Ph. Zeitoun et al, Nature, 431, 2004*)

SOLID TARGETS

ADVANTAGES :

- High output energy (10 µJ to 10 mJ depending of the IR pulse duration)
- Broad soft x-ray lines ⇒ potentially 100 fs seeded SXRL
- Lasing demonstrated down to 3 nm

DISADVANTAGES :

- Strong ASE that may dominates the seeded SXRL
- Strong refraction
- Difficult localisation of the gain

(*T. Ditmire at al, Phys. Rev. A, 1995*
Wang et al, Phys. Rev. Lett, 97, 2006)

TUIXS is an FP6-NEST-ADVENTURE project devoted to

Tabletop Ultra-Intense XUV Sources
for femto-biology and related applications

Our goal with current laser facilities

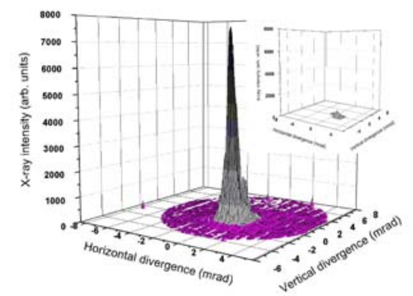
1mJ, 100fs at 13nm

(10^{18}W/cm^2 at 40xDiffLimit)

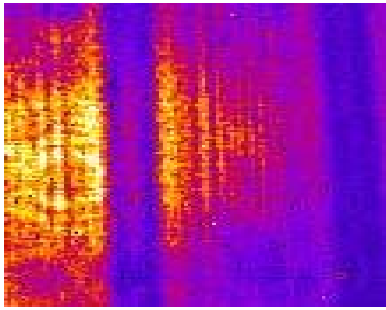
Participants are:

M. Fajardo, CFP-IST (coordinator);
Ph. Zeitoun, LOA (deputy-coordinator
J. Hajdu, U. Uppsala (deputy-coordin
H. Merdji, CEA;
B. Rus, PALS;
A. L'Huillier, U. Lund;

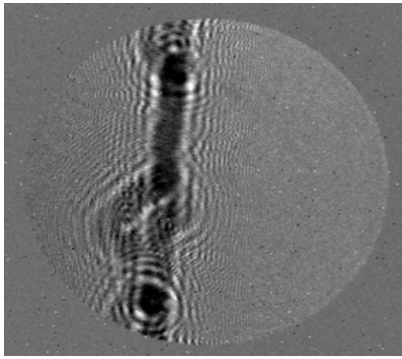
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



We are building
Second generation X-ray lasers
by seeding a High Harmonic in a plasma amplifier.



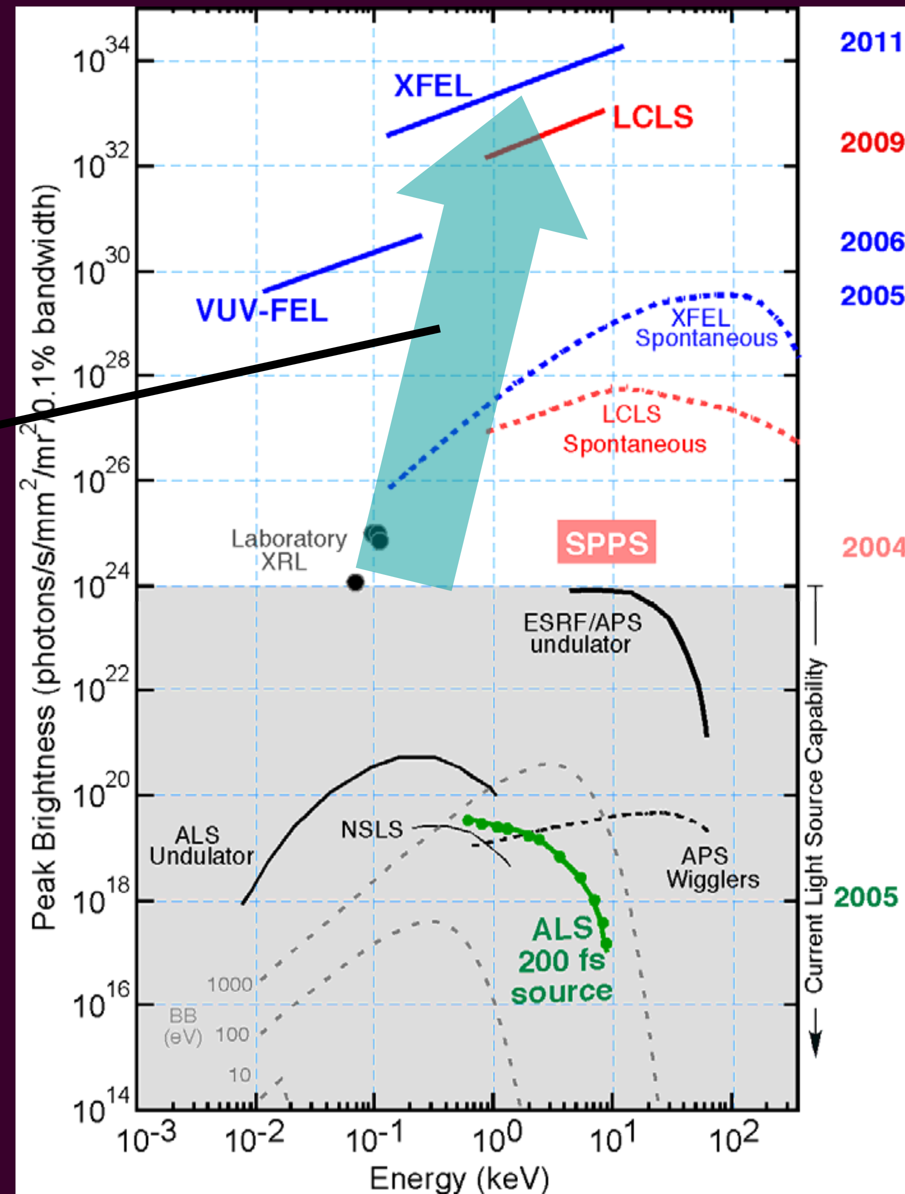
Our experience shows that the seeded pulse **keeps the optical properties** of the HHG:
Polarization, Coherence, short pulse
(see Ph. Zeitoun et al, Nature 2004)



The requirements of the source are being driven by applications
We are currently developing new

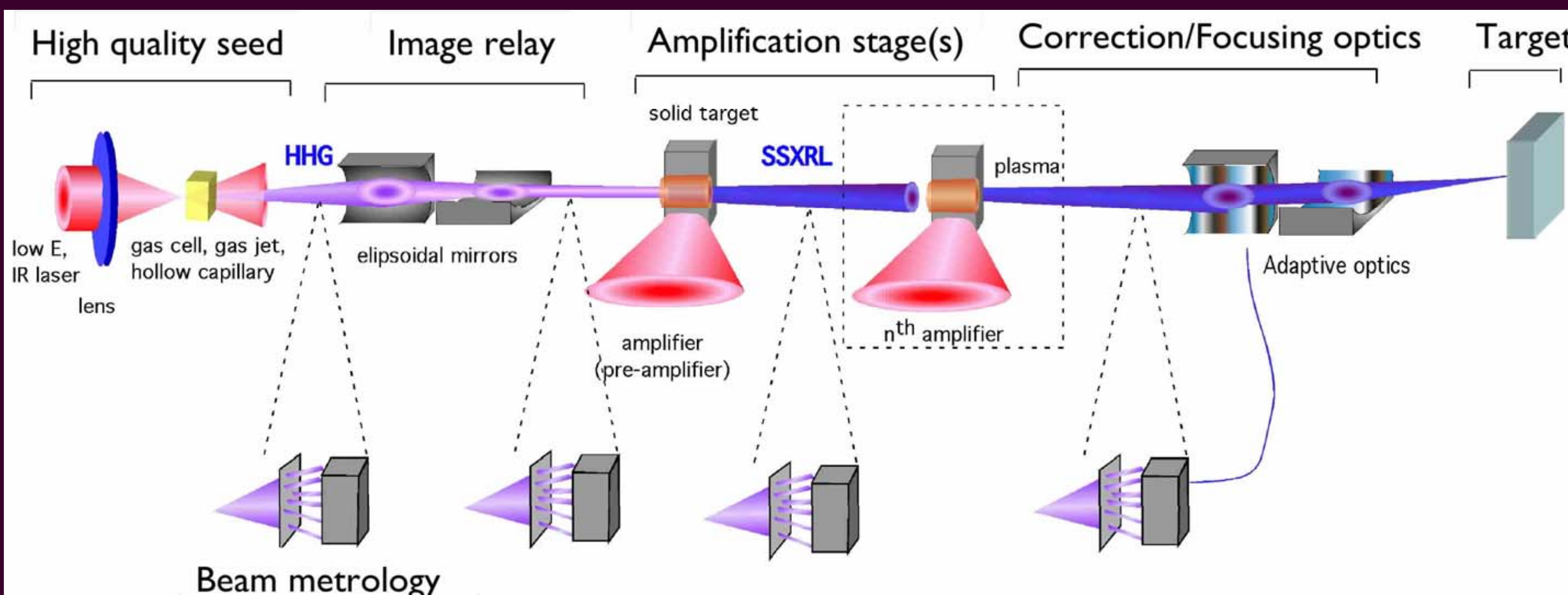
Bridging the gap between current XUV lasers

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

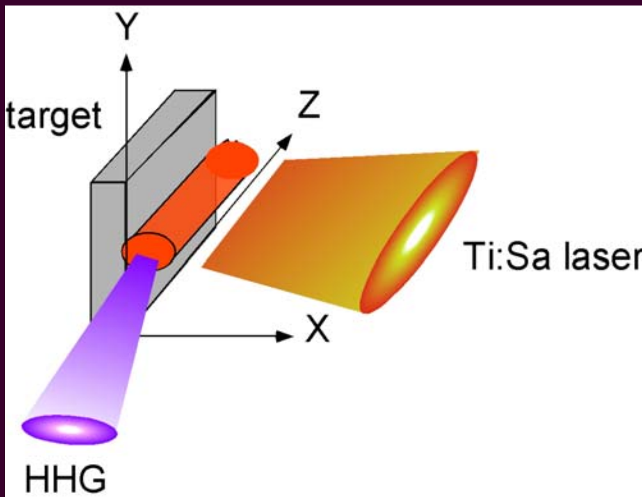


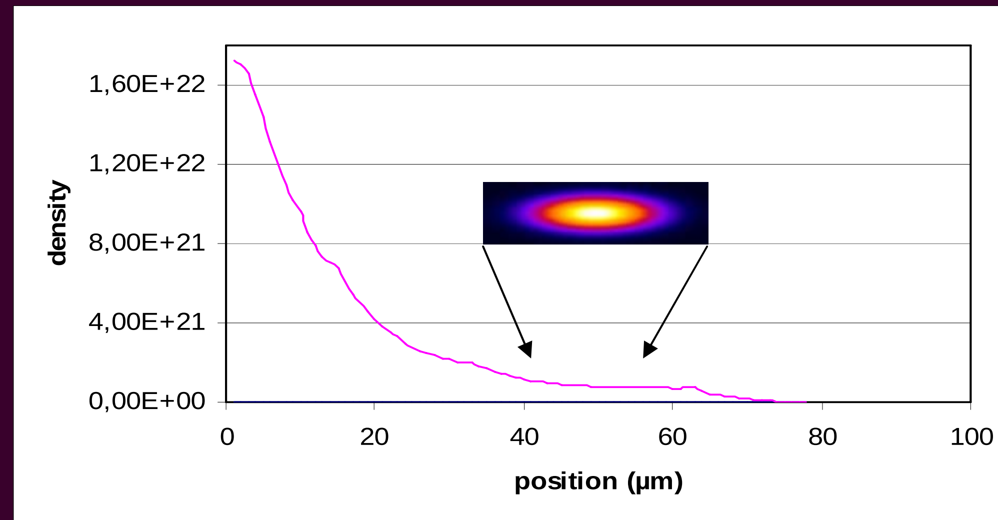
Challenges for an XUV laser chain

1. Optimizing the amplifier
2. Optimizing the seed
3. Controlling the optical quality
4. Preparing for ultra-high intensity e

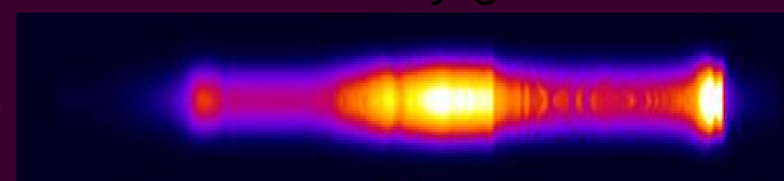


Refraction is a major problem when it comes to solid targets

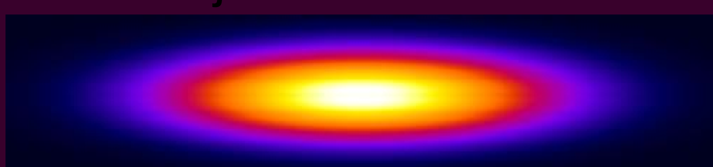




Simulated density gradient



Injected beam

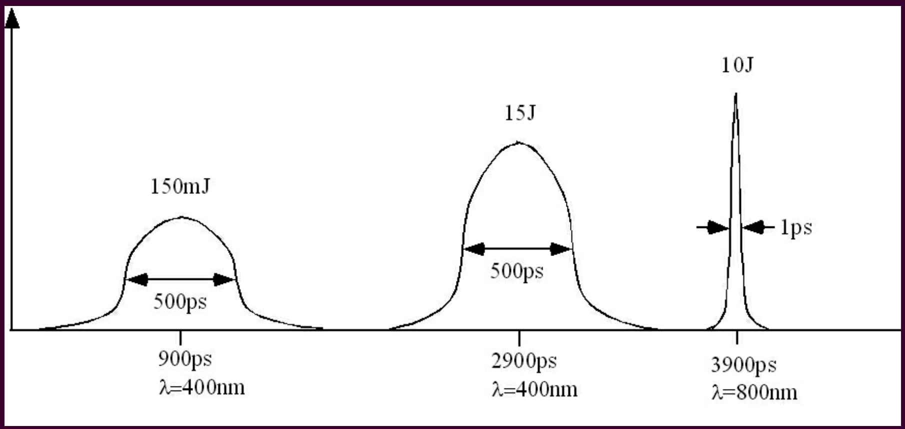


1 mm

Linear density gradient

If the gradient is not homogeneous, the beam is degraded

Control of the amplifier hydrodynamic

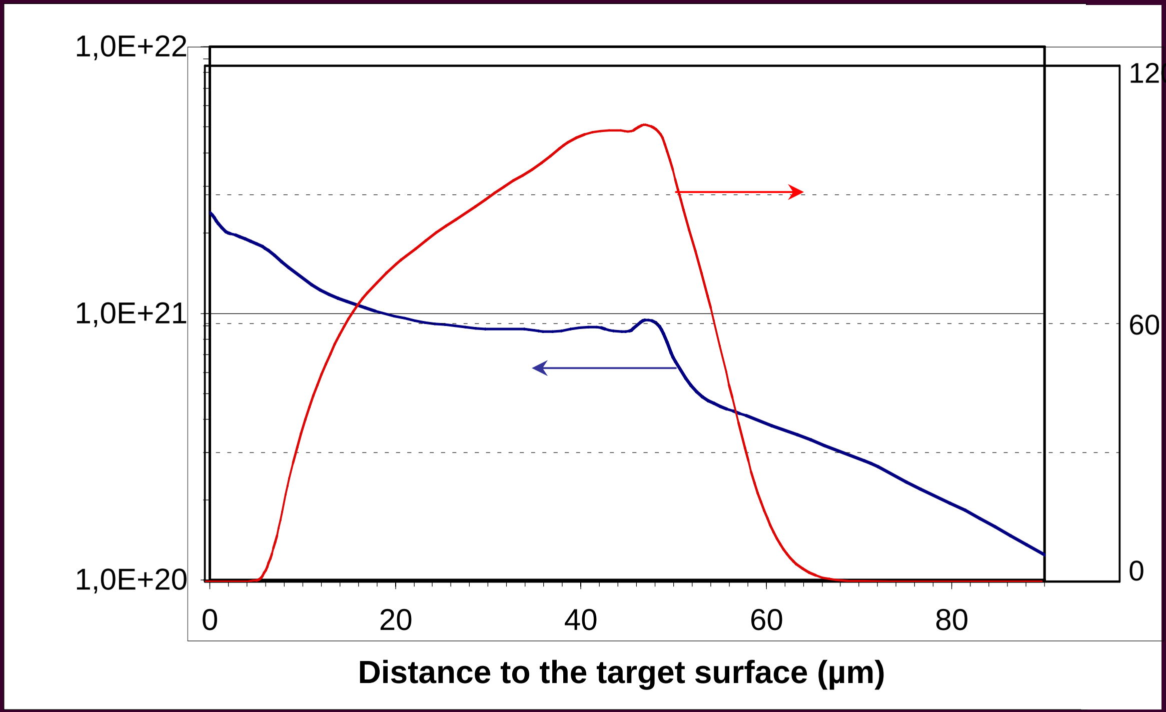


- Slab Fe, J=0-1, 25.5 nm

Pump laser: Ti:Sa, 10×0.2 mm² focal line

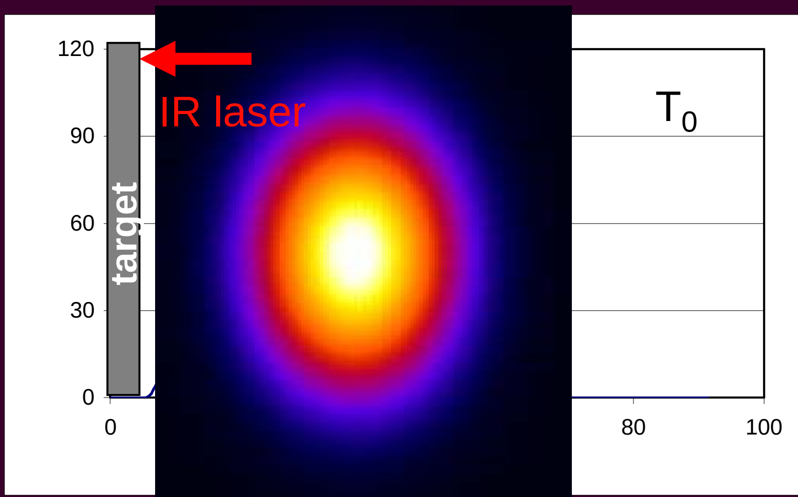
- Modelled with EHYBRID (1.5D code)

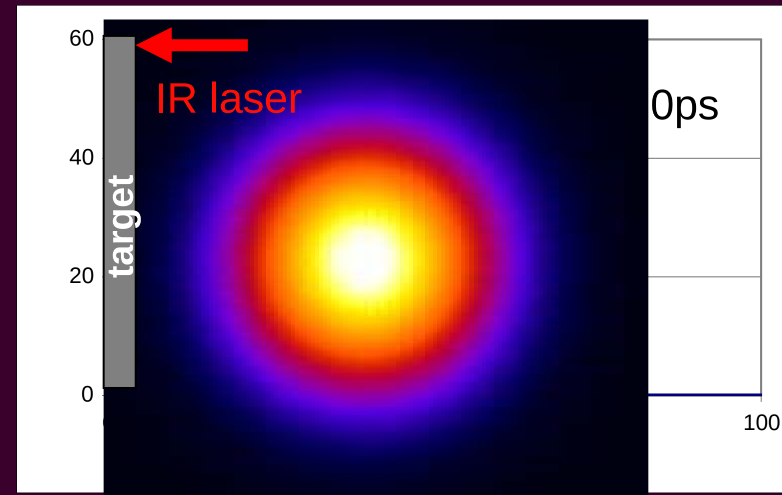
- Homogeneous and dense plasma over the gain region



The gain imprints the output beam

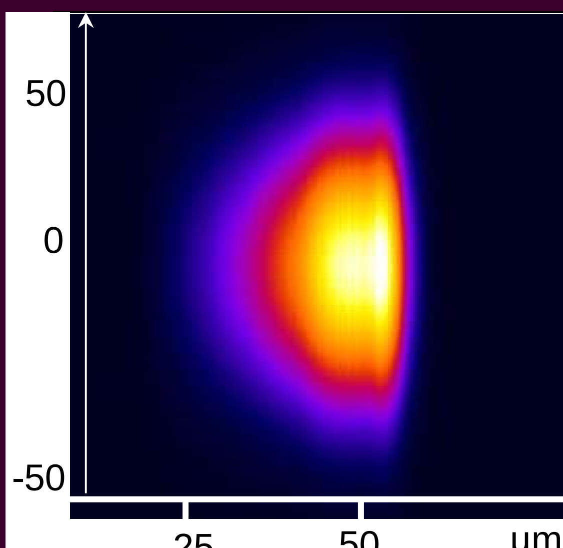
Ne(x,y) = cst



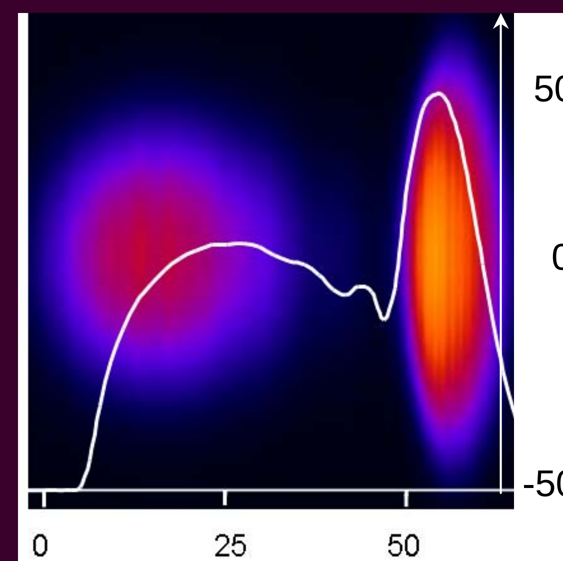


3D ray-trace modelling
10^8 rays
10 parallel computers

$F_{in} = 10^{-3} \times F_{sat}$
$F_{out} \sim F_{sat}$



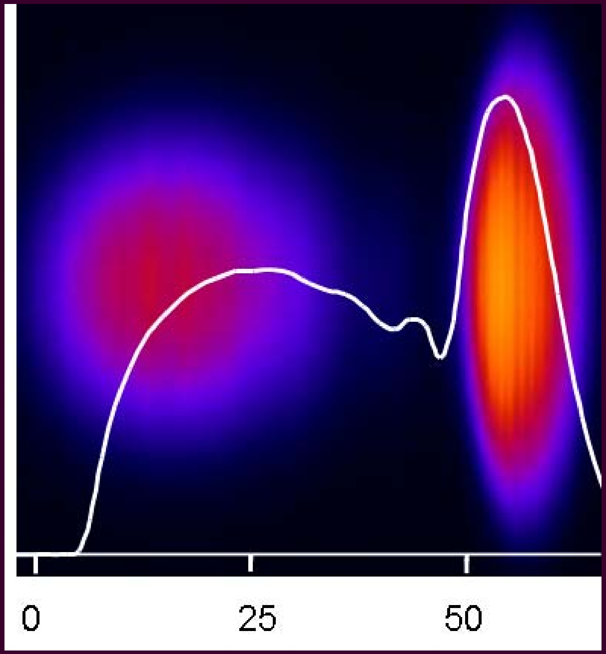
Exit plane



Exit plane

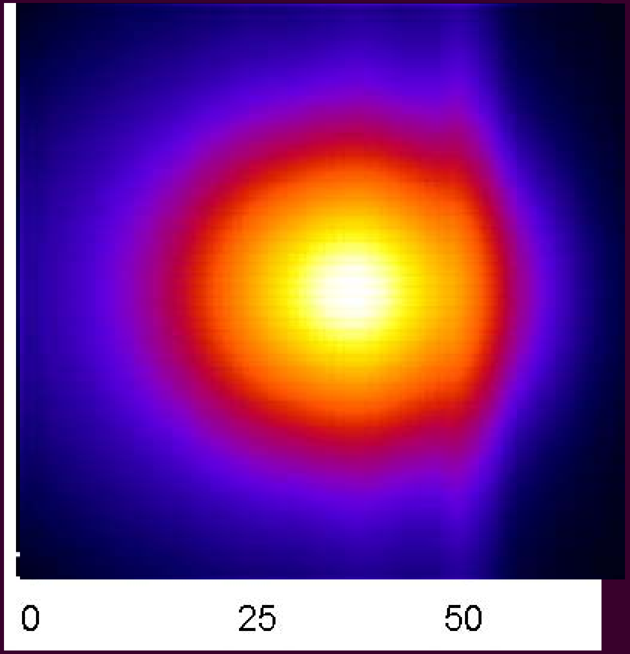
Saturation smooths out the gain inhomogeneities

Weakly saturated



$F_{in} = 10^{-3} \times F_{sat}$
$F_{out} \sim F_{sat}$

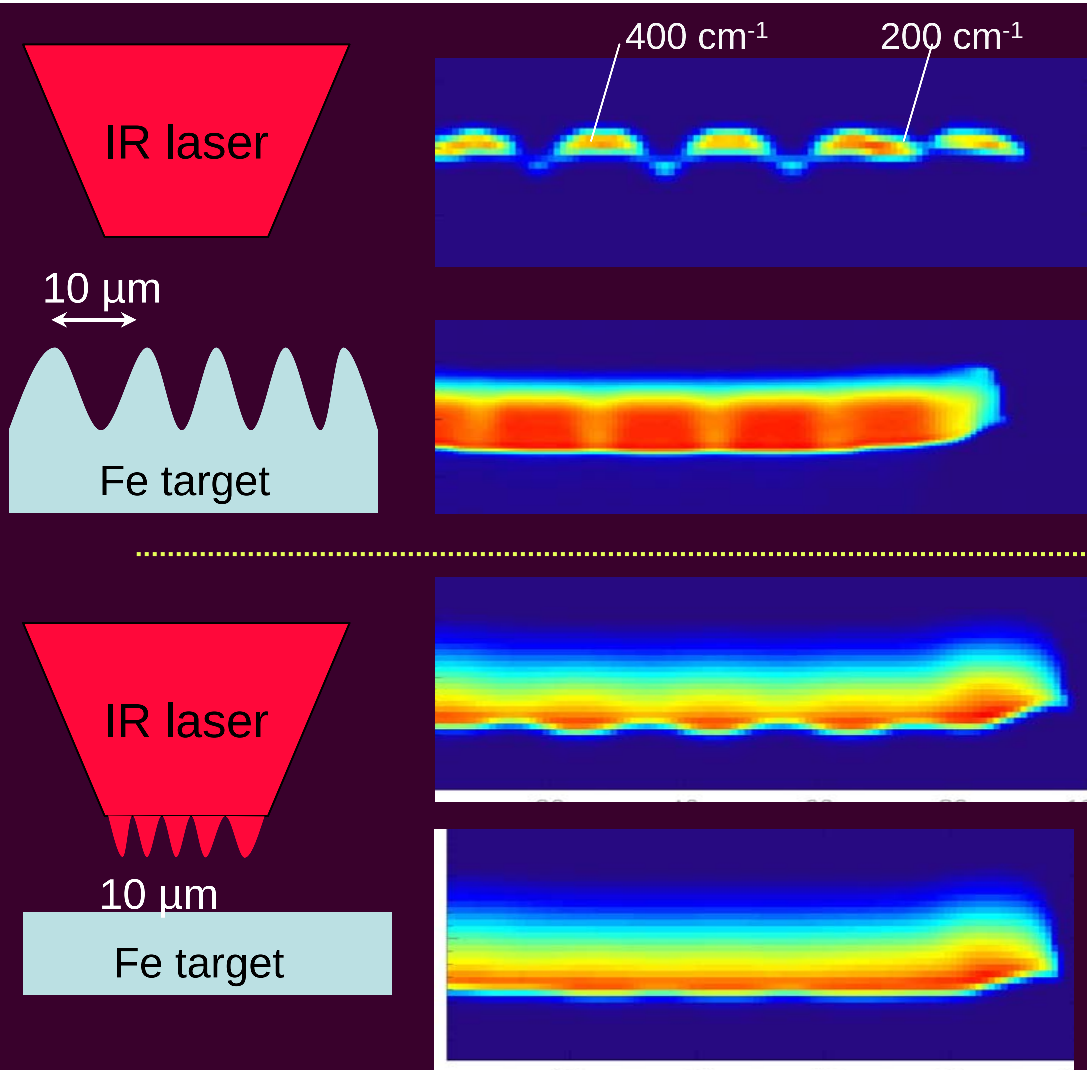
Deeply saturated



$F_{in} = 10^{-1} \times F_{sat}$
$F_{out} \sim 5 \times F_{sat}$

- Seeding angle is also a useful parameter for smoothing the output beam

2D adaptive Mesh refinement code is used to find the best plasma conditions



Gain transverse profile

With 5 µm depth

With 1 µm depth

With ΔI/<I> = 0.15

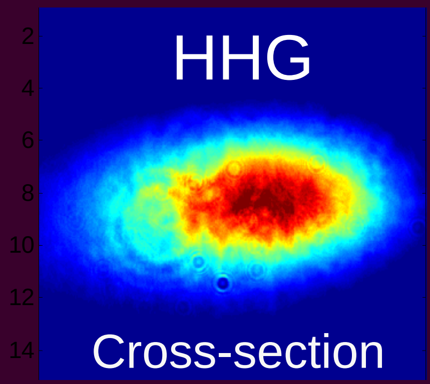
With ΔI/<I> = 0.05

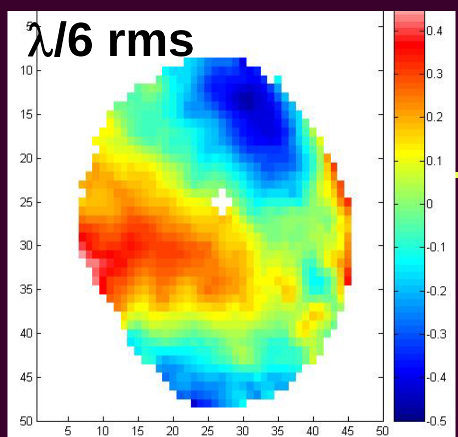
E. Oliva et al, to be published

We have started benchmarks using tailored plasmas at PALS

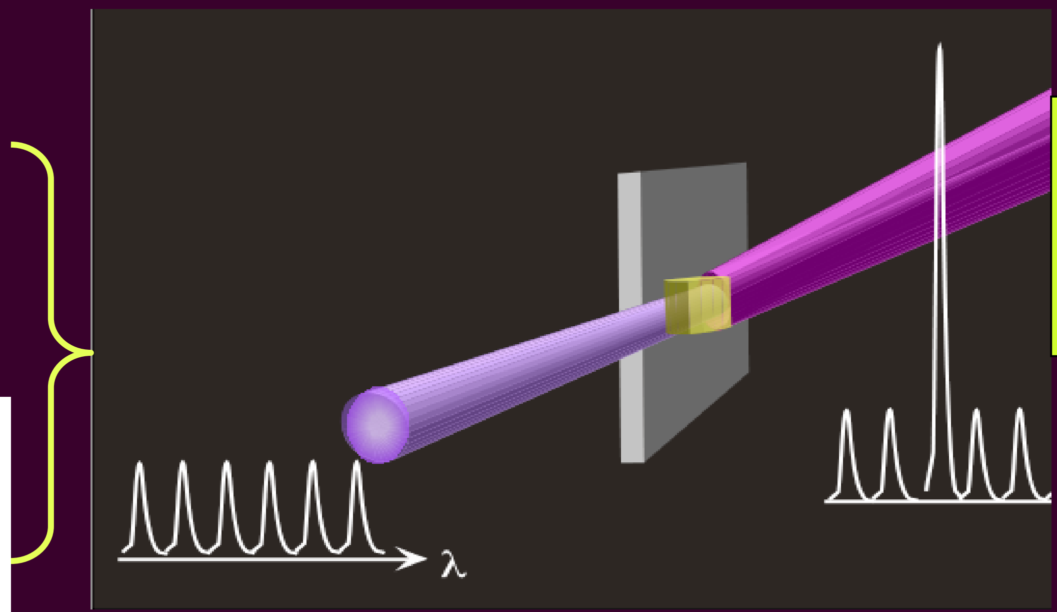
HHG is an adapted seed

N.A. =0.1, λ=13 nm ➡ D.L. focal spot = **0.3 µm FWHM (I > 10^{19} Wcm^{-2})**





Measured wave front



Output phase and amplitude ?

- Good wave front and beam profile
- Strong emission demonstrated down to 4 nm (Zepf et al, Nature 2006)

Seeding in Solid plasma has been demonstrated by J. Rocca’s group

Wang et al, PRL 97, 123901 (2006)

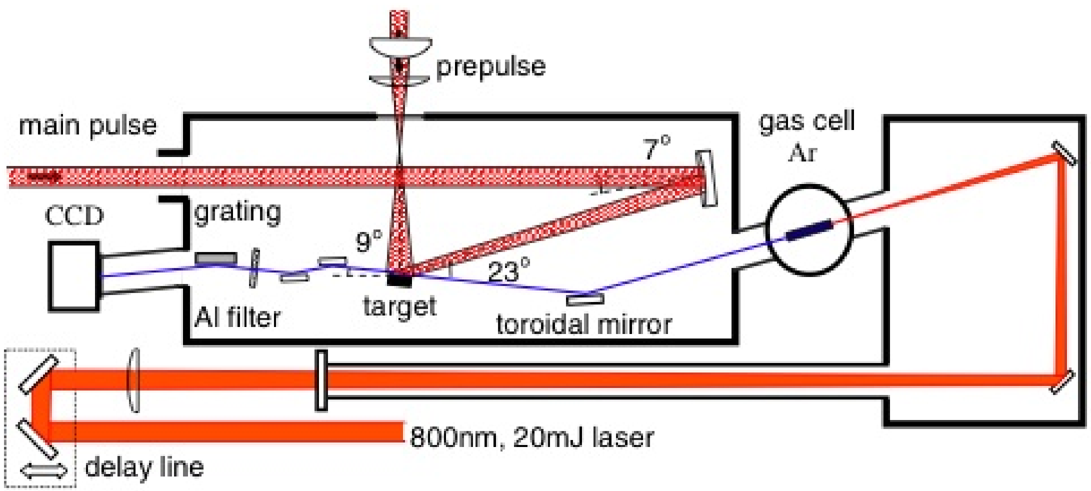
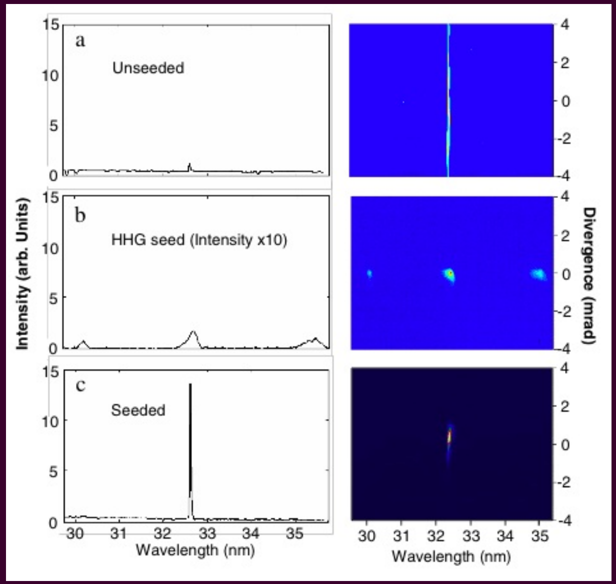


FIG. 1 (color online). Schematic representation of the seeded soft-x-ray-laser amplifier based on a grazing incidence pumped plasma.

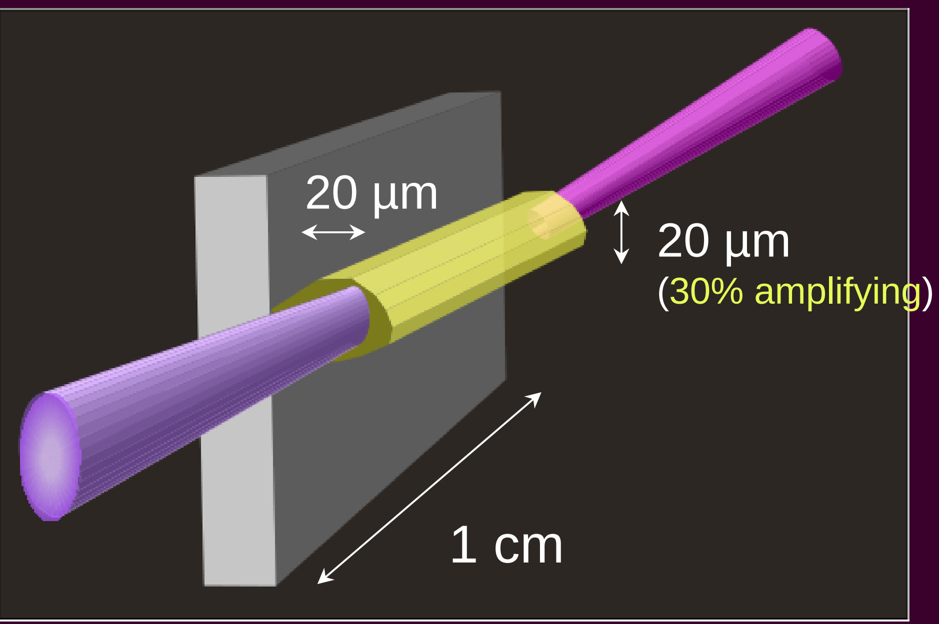


Ne-like Ti at 32.6nm

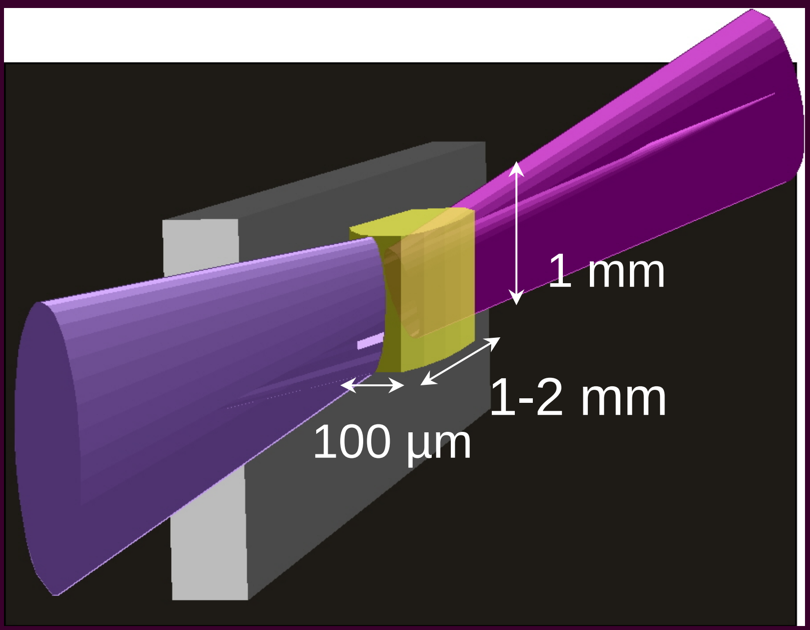
How far can we go with seeded XRL?

F_{sat} ~0.1 J/cm^2 *(from measurements: Cassou et al…)*

Classical scheme (rod)



New scheme (slab)



$S_{sat} = 4*10^{-6}$ cm^{-2} $\Rightarrow$ E~0.4 µJ

Wan et al, PRL 2006

$S = 10^{-3}$ cm^{-2} $\Rightarrow$ E_{sat}~ 0.1 mJ

E_{pump} ~ 10-20 J

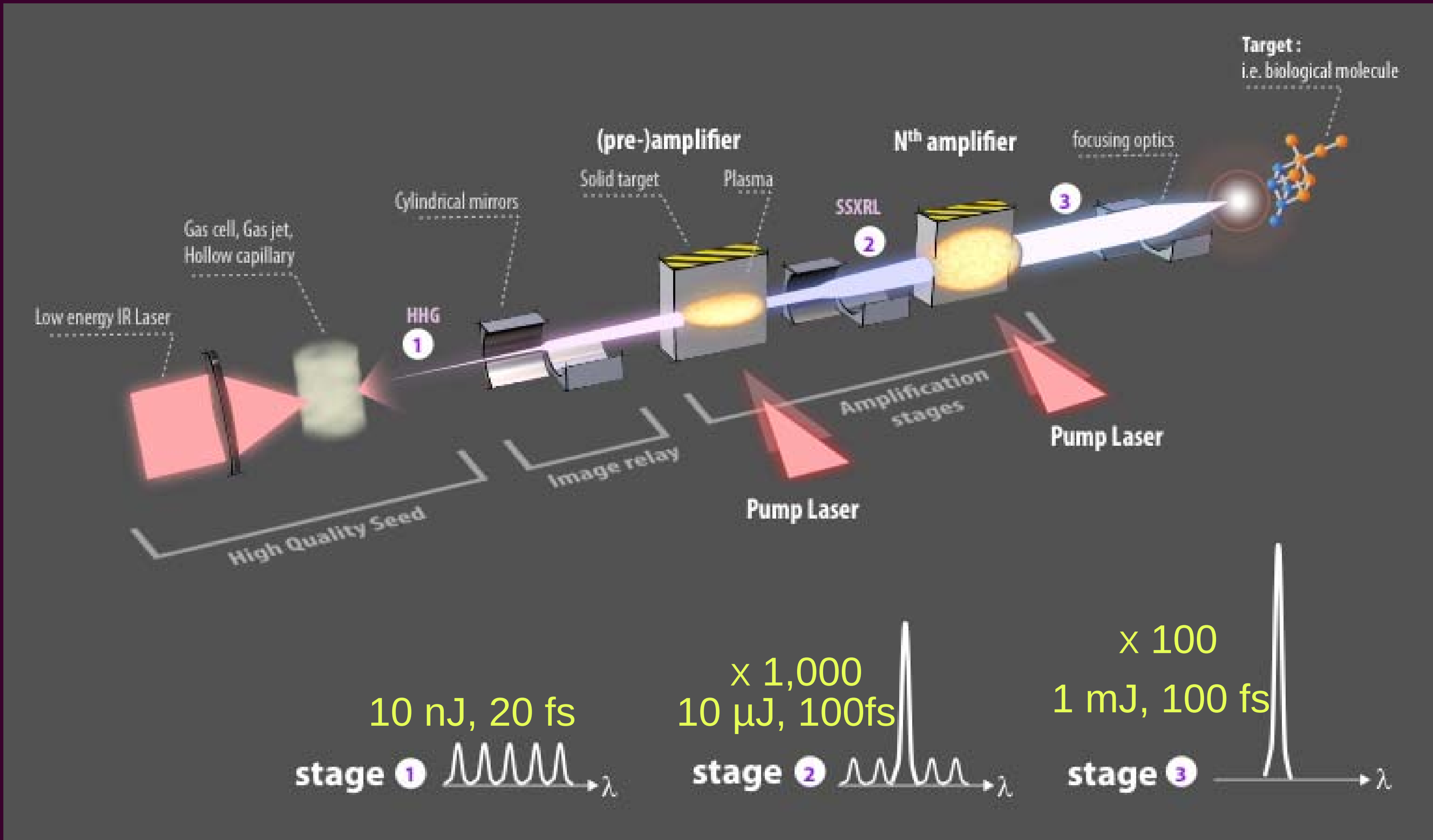
- By increasing the active surface :
  - The pumping efficiency is enhanced
  - The ASE will remain at a negligible level (and very divergent)

Is that it?

- Tabletop seeded XRL are a promising -affordable- tool for small-scale laboratories
- Market niche: rep rate, ultra-short, really short λ, tunable?
- Plasma-based XRL specificity is the amount of energy that is stored in the plasma that can be extracted
- No other XUV source can deliver same Nphotons

Multi-stages soft x-ray amplification chain is required

$F_{out}/F_{in} = 1{,}000 \Rightarrow E_{in} = 1\ \mu J$ but $\Delta\lambda_{HHG}/\Delta\lambda_{sxRL} = 10^{-2}$ for HHG $\Rightarrow F'_{in} = 100\ \mu J$ (!!)



- No limit on the output energy as long as we have enough pump energy⇒ ELI !

ELI will generate shorter, shorter, and more intense beams

- Shorter wavelength (4 nm and below):

S. Maxon et al, *High gain x-ray lasers at the water window*, Phys. Rev. Lett., 70, 2285 (1993)

G= 45 cm^{-1} with 2ω (λ=0.53 µm; 5×10^{13} Wcm^{-2}; 80 ps) + 2ω (λ=0,53 µm; 2×10^{15} Wcm^{-2};1 ps)

$\Rightarrow$ Pump energy for a 2×2 mm^2 focal spot = (50% doubling efficiency) =160J +320 J (about 1,5 ELI arms).

$\Rightarrow$ Temporal shaping is possible (prepulse, pedestal etc) that dramatically increases the pumping efficiency.

- Shorter duration (sub-100 fs):

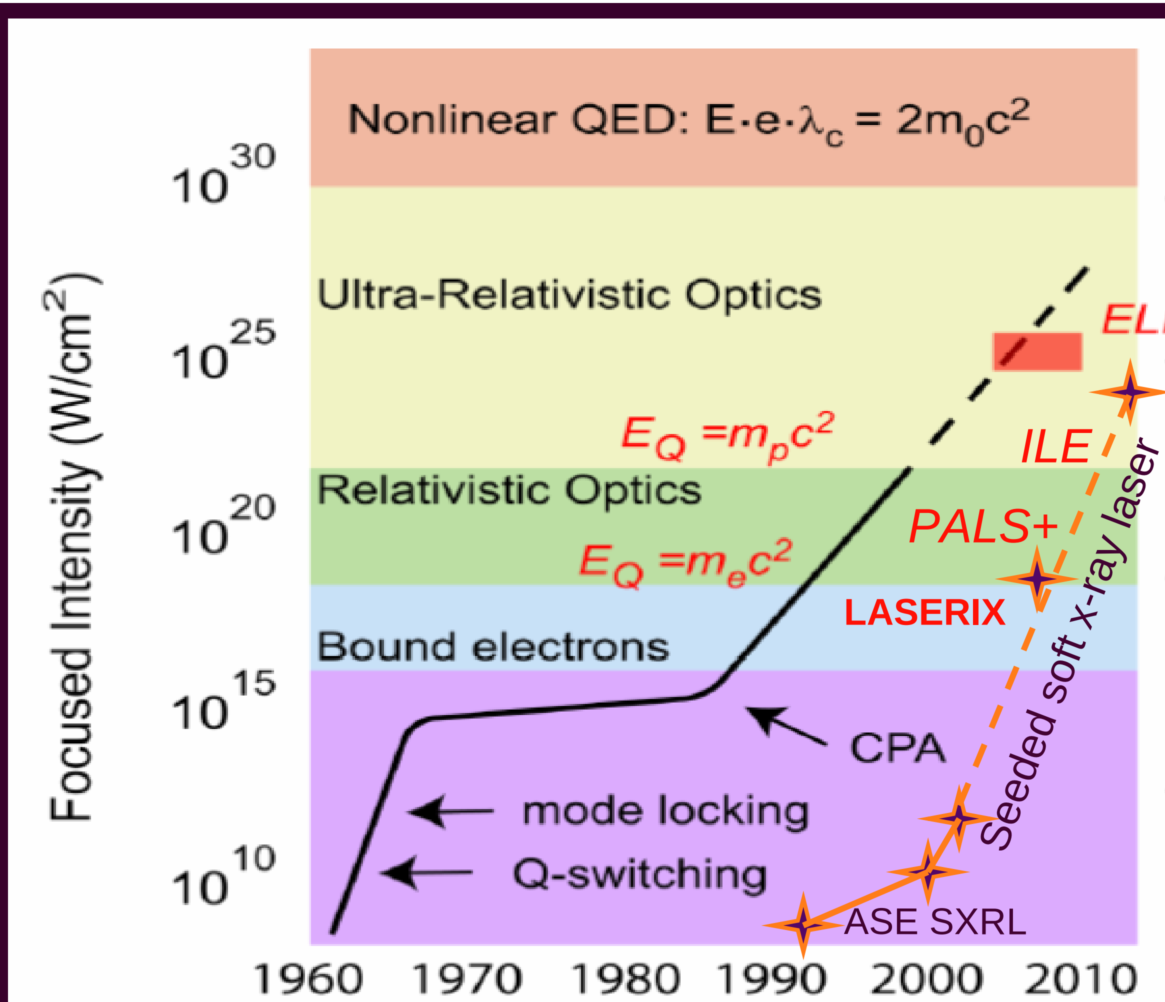
$\Delta\lambda_{Doppler} \propto (T_i)^{1/2} \Rightarrow$ no realistic scaling law (depend on the experiment).

T_i~100 eV I=5×10^{12} Wcm^{-2} (Ne-like Fe @25.5 nm) $\Rightarrow$ T_i~800 eV I=5×10^{13} Wcm^{-2} $\Rightarrow$ $\Delta\tau/3$

- More intense

$F_{sat} \propto 1/\lambda^4 \Rightarrow F_{sat}$~0.1 J/$cm^2$ @25 nm $\Rightarrow$ 152 J/cm^2 @4 nm (other parameters assumed to stay constant) $\Rightarrow$ Esat = 150 mJ $\Rightarrow$ I = 3×10^{22} Wcm^{-2} (NA=0.1)

The seeded soft x-ray laser time chart



- Tools, both numerical (2D hydrocode + 3D ray-tracing) and experimental (optics, XUV wave front sensor + XUV adaptive optics), are close to be ready.

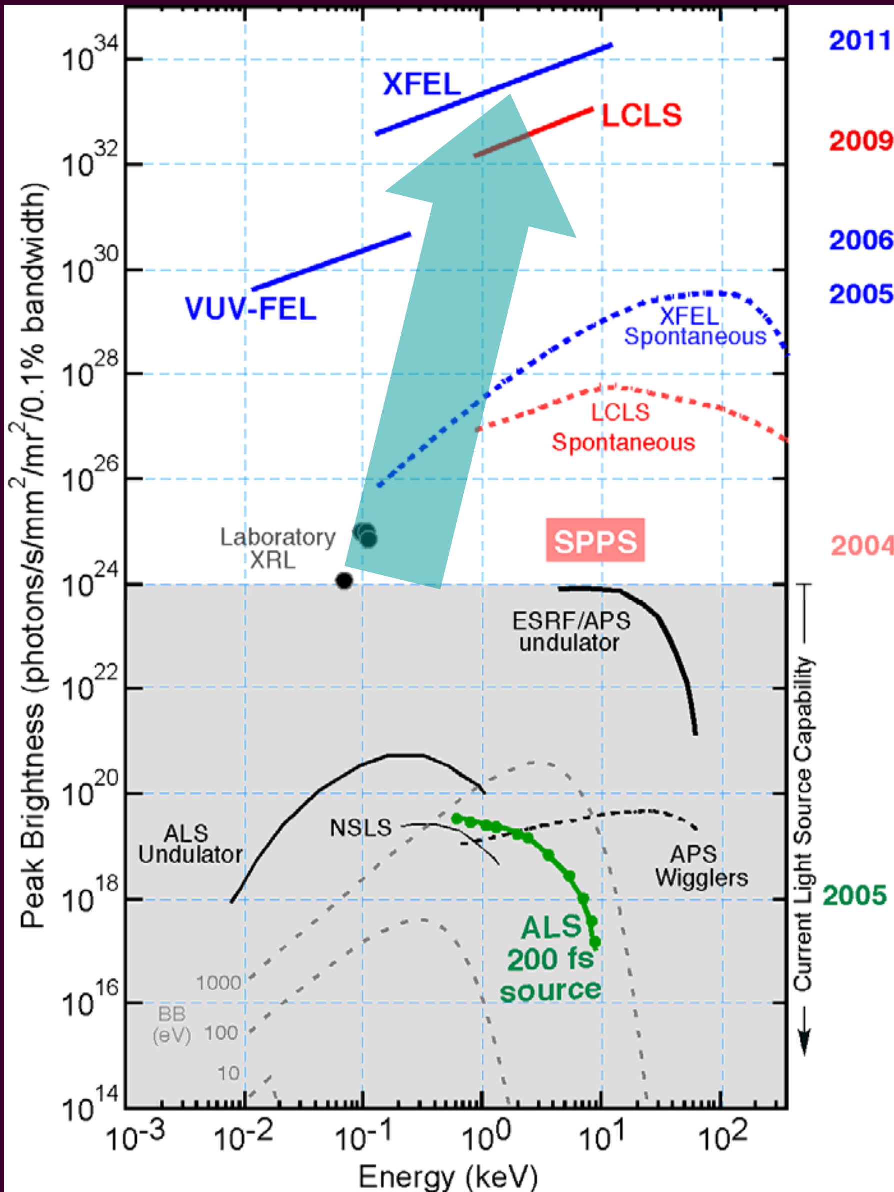
We will begin to explore completely uncharted territory

- ***HED studies:***
  Producing plasmas with XRL
  Warm Dense Matter

- ***Pump-Probe experiments with laser-produced plasmas:***
  Fusion related high density maps

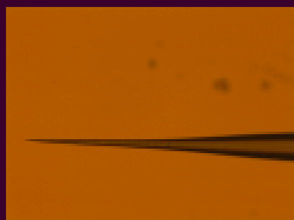
- ***Breakthrough 3D imaging (time/space resolved)***

The plasma community is "single-shot" and demands E

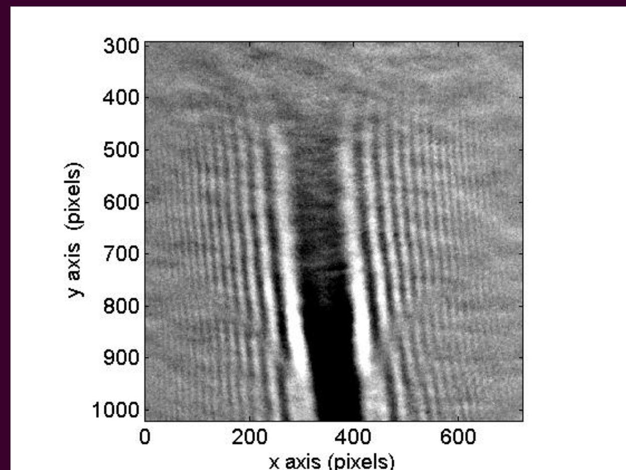


Towards single-shot XUV Holography

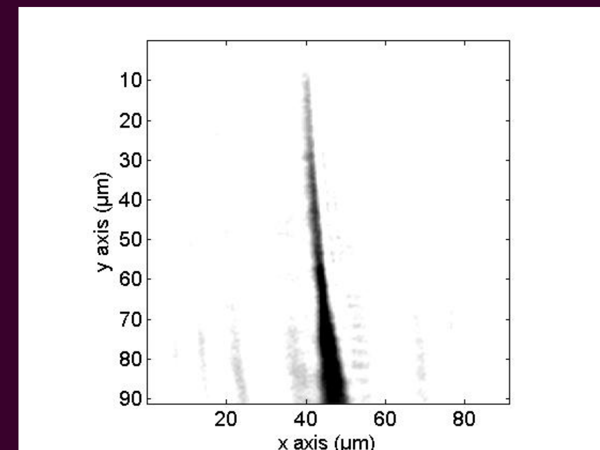
Tips with apex radius 50nm



hologram



reconstruction

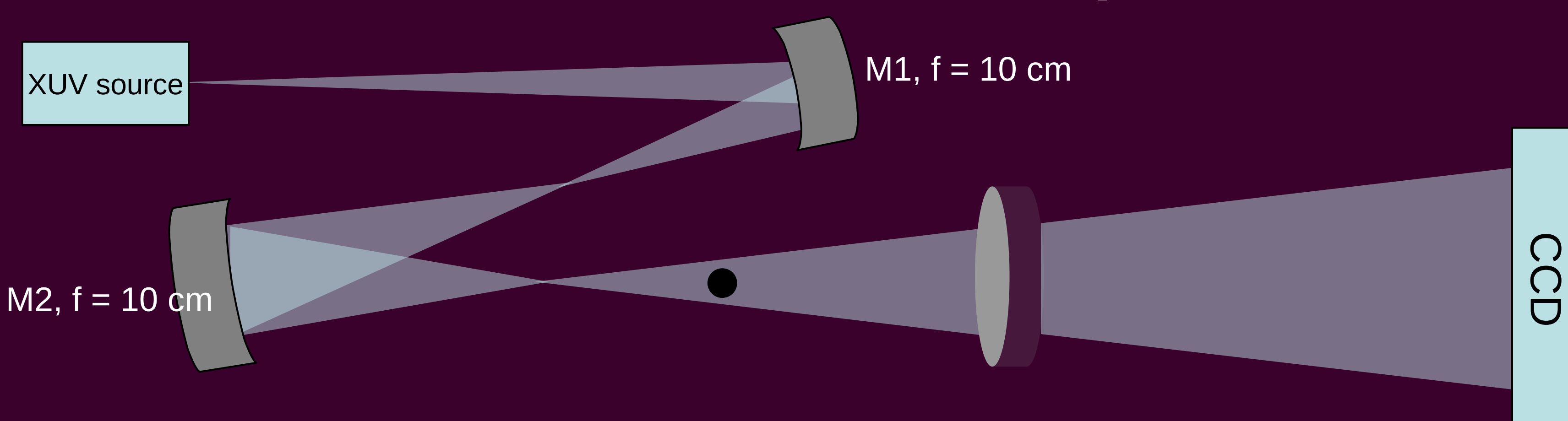


<u>Theorical resolution</u>

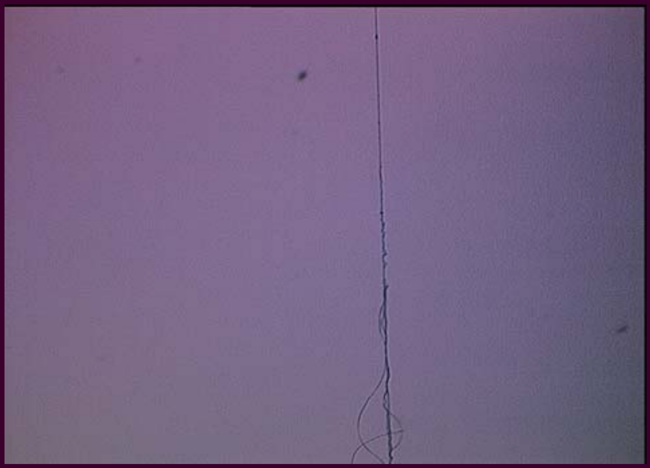
N.A.=0.025=>R_l=630 nm

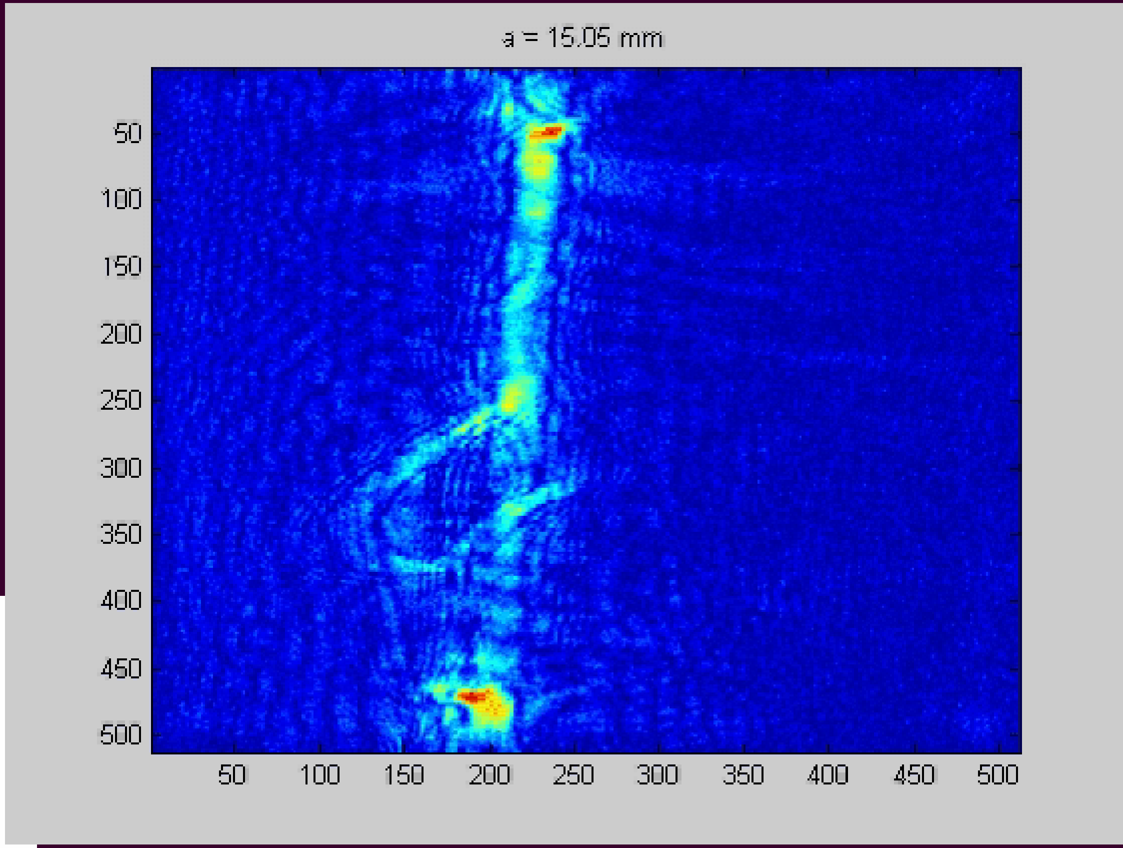
<u>Experimental resolution</u>

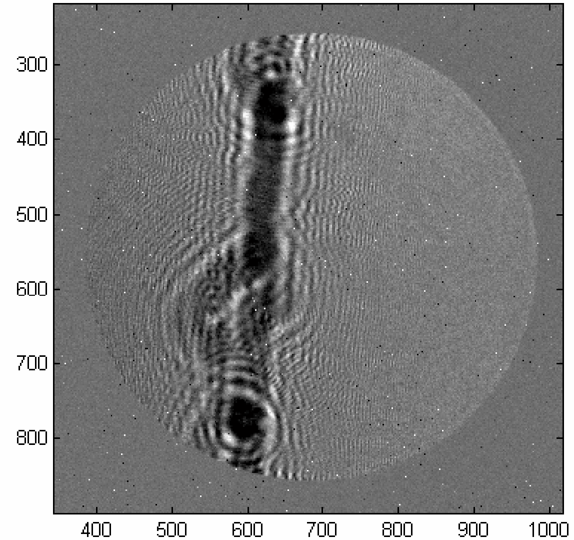
R_l = 800 nm



Hologram reconstruction reveals depth of field







Courtesy Jean-Pascal Caumes

QuickTime™ et un décompresseur TIFF (Uncompressed) sont requis pour visionner cette image.

Conclusion

1. Seeding Plasma amplifiers has been demonstrated

2. It combines high photon number with short pulse and optical qualities

3. With larger drivers (ELI, HIPER) come lower wavelengths, shorter duration, and up-scalability in Energy

4. It is the natural road to High-Power Soft-XRL

Thank you