High Contrast Femtosecond Laser-driven K-shell X-ray Source in Imaging Application

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Outline

1. Current situation of fs laser-based hard x-ray source in medical imaging

2. Improved source using solid target

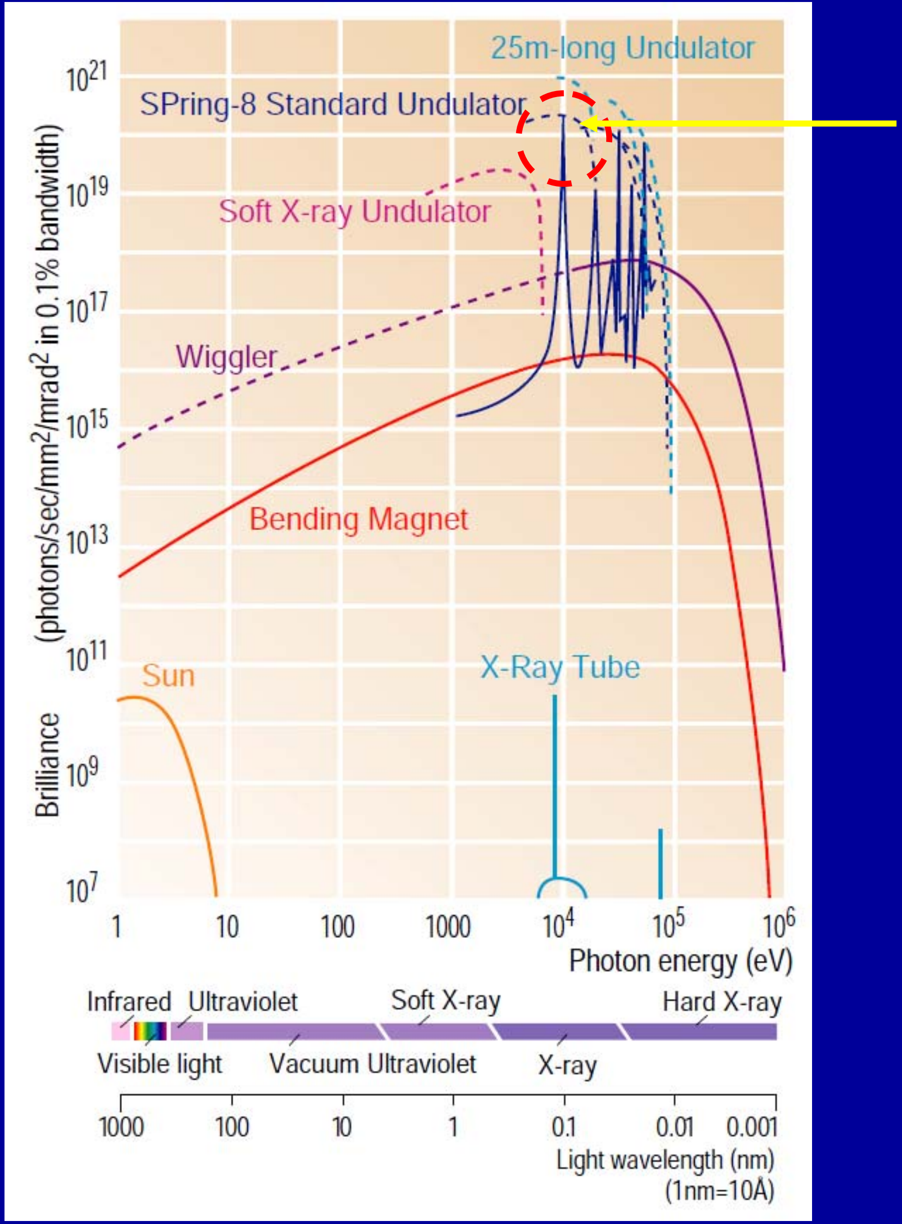
3. Improved source using cluster target

4. Summary

X-ray generation by ultrafast laser

- continuous bremsstrahlung emission (depends on temperature of hot electrons)
- characteristic x-ray emission lines (depend on target chemical composition)
- x-ray burst duration $\tau < 1$ ps (depends on optical pulse duration)
- x-ray focal spot size (depends on optical spot size and pulse duration); could be as small as ~2 μm

Source compare..



LB x-ray source

- The peak brightness is close to the 3rd generation synchrotron

With:

ps pulse duration

Monochromatic

Micro-m source size

Potential application

LB source is very useful for various fields:

Life Science: Atomic structure analysis of protein macromolecules; Mechanism of time-dependent biological reactions; Dynamics of muscle fibers

Materials Science: Precise electron distribution in novel inorganic crystals; Structural phase transition at high pressure / high or low temperature; Atomic and electronic structure of advanced materials of high Tc superconductors, highly correlated electron systems and magnetic substances; Local atomic structure of amorphous solids, liquids and melts

Chemical Science: Dynamic behaviors of catalytic reactions; X-ray photochemical process at surface; Atomic and molecular spectroscopy; Analysis of ultra-trace elements and their chemical states

Earth and Planetary Science: *In situ* X-ray observation of phase transformation of earth materials at high pressure and temperature; Structure of meteorites and interplanetary dusts

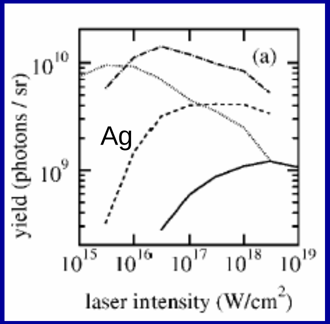
Environmental Science: Analysis of toxic heavy atoms contained in bio-materials; Development of novel catalysts for purifying pollutants in exhaust gases; Development of high quality batteries and hydrogen storage alloys

Industrial Application: Characterization of microelectronic devices and nanometer-scale quantum devices; Analysis of chemical composition and chemical state of trace elements; X-ray imaging of materials; Residual stress analysis of industrial products;

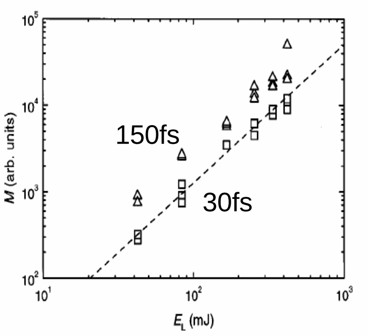
Medical Application: Application of high spatial resolution imaging techniques to medical diagnosis of cancers and capillaries

Difficulties for LB x-ray… (I) Kα efficiency (η_K)

Using normal contrast laser…



Obstacles of Kα x-ray enhancement when pulse width < 100fs



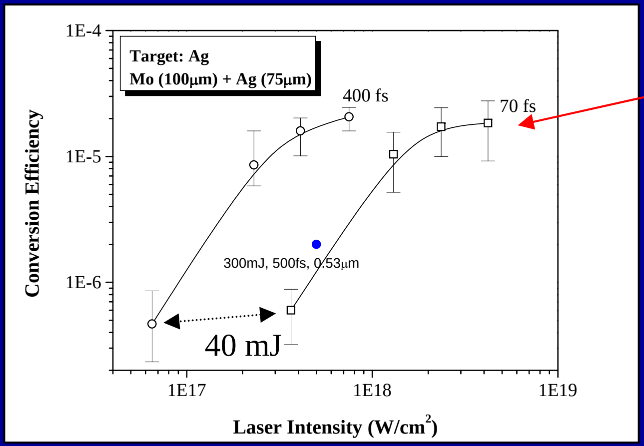
η_K drops as higher laser intensities
---X-ray re-absorption

e.g: Ch. Reith et al., PRL 84, 4846(2000)
L=0.3, RA, Ag I_{opt}~10^{17} W/cm^2

D. C. Eder et al., Appl. Phys. B 70, 211(1999)

η_K drops as shorter pulse width

e.g: M. Schnurer, et al., PRE, 61, 4394(2000);
J. Appl. Phys. 80, 5604(1996)

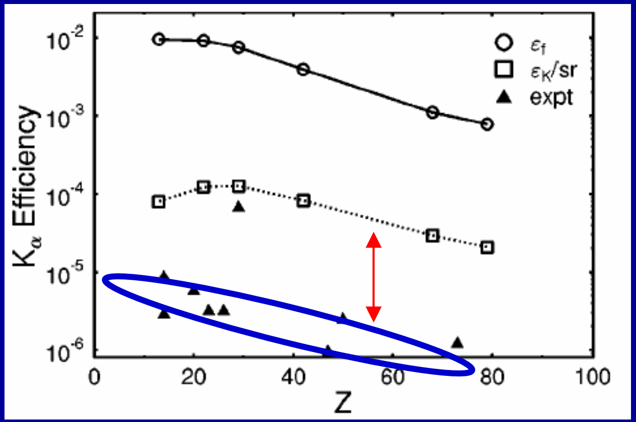


L. M. Chen, PoP 11, 4439(2004)

Saturation appears!!

Not optimized！！

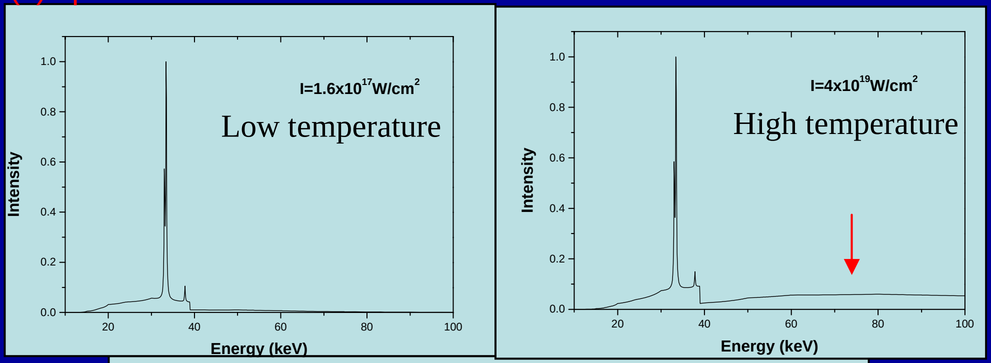
10 times lower than theoretical prediction



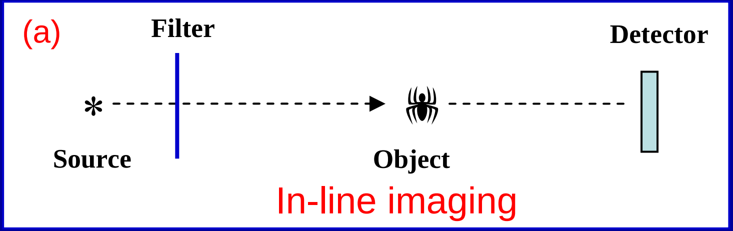
D. Salzmann, PRE 65, 036402(2002)

Difficulties of LB x-ray… (II) Spectrum contrast

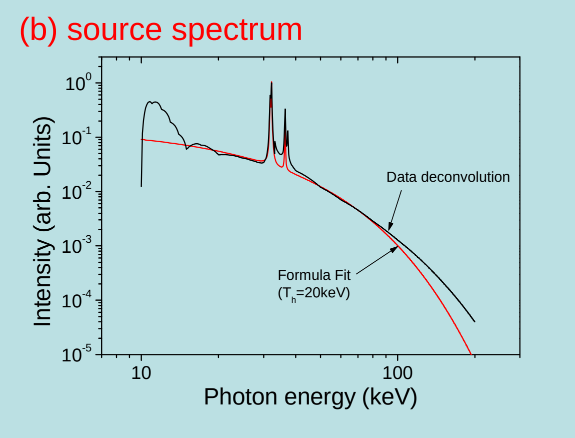
(c) spectrum after filter



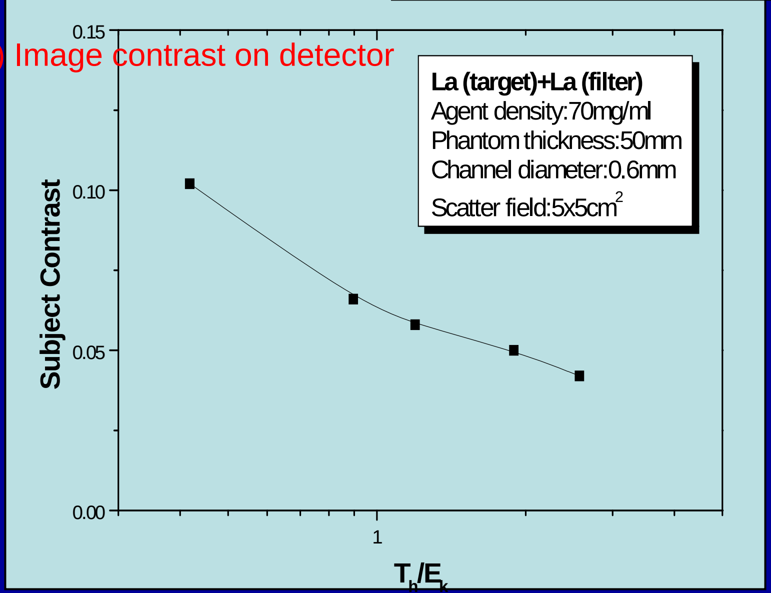
(a)



In-line imaging



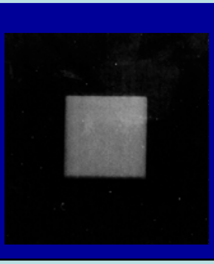
(b) source spectrum



(d) Image contrast on detector

Example:

Experimental mammography



Phantom 2 cm
25/75 (gland/adipose)
composition

	790 nm laser	X-ray tube
KT_h (keV)	25	28 kV_p
Imaging contrast	0.24	0.60

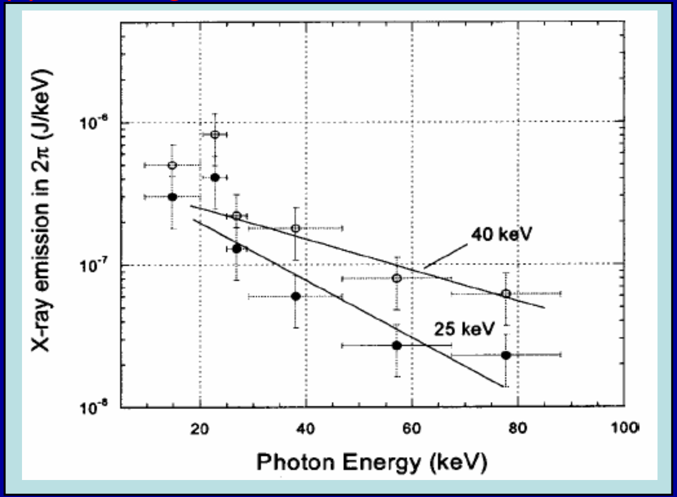
Worse !!

- Imaging subject contrast becomes worse When x-ray energetic tail increasing

---Kα source with less background is necessary

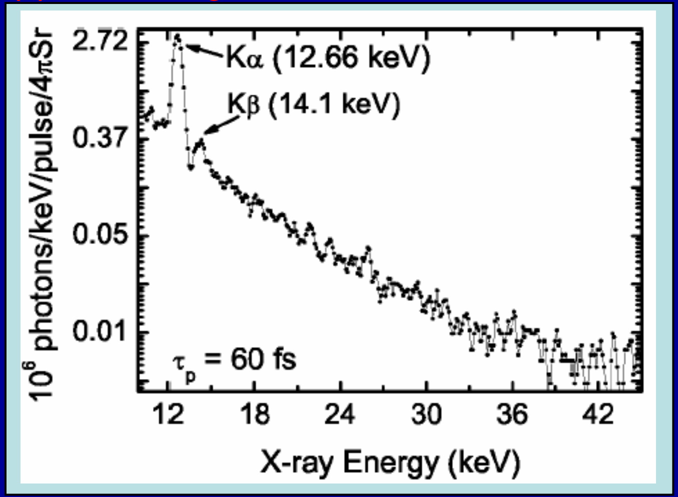
Spectrum contrast…

(a) Solid target



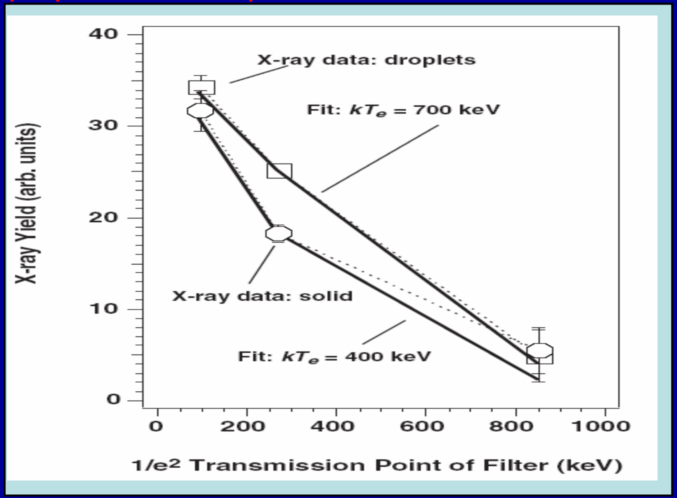
PoP 11, 4439(2004)

(b) Cluster target



PoP 11, 3491(2004)

(c) liquid micro-droplet



J. Phys. B 34, L313(2001)

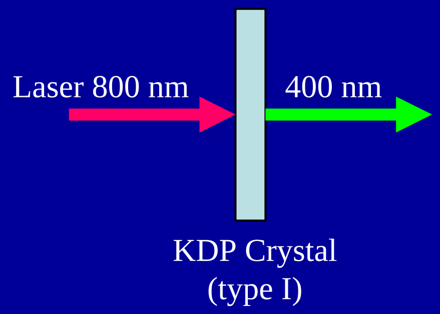
	Solid target	droplet	clusters
Source C.	bad	worse	bad
K efficiency	~10^{-5}-10^{-4}	~10^{-5}	~10^{-6}

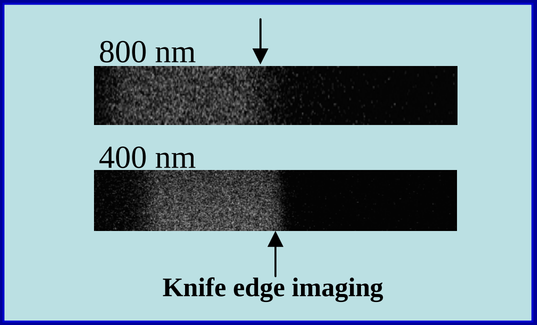
LB x-ray source is seriously limited in imaging application !!

Stronger,cleaner and smaller source is necessary

How to improve?

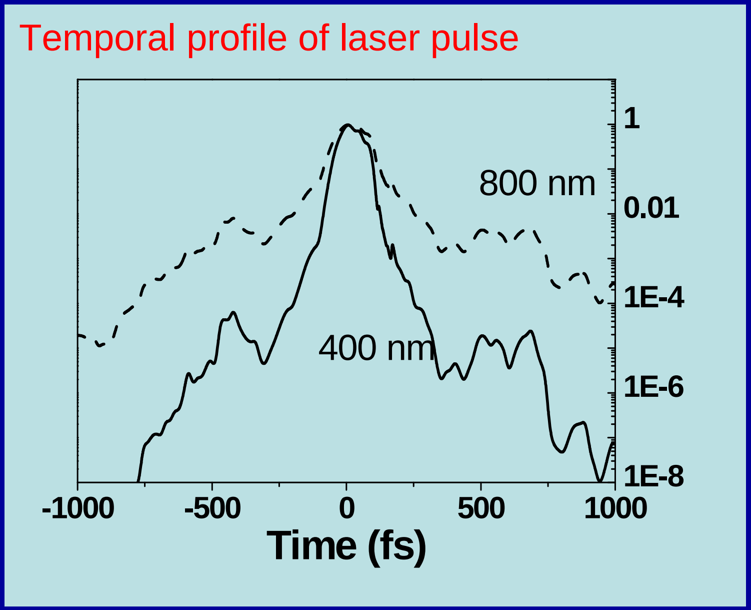
Laser longitudinal compress via frequency doubling





X-ray source size detected vs. laser contrast

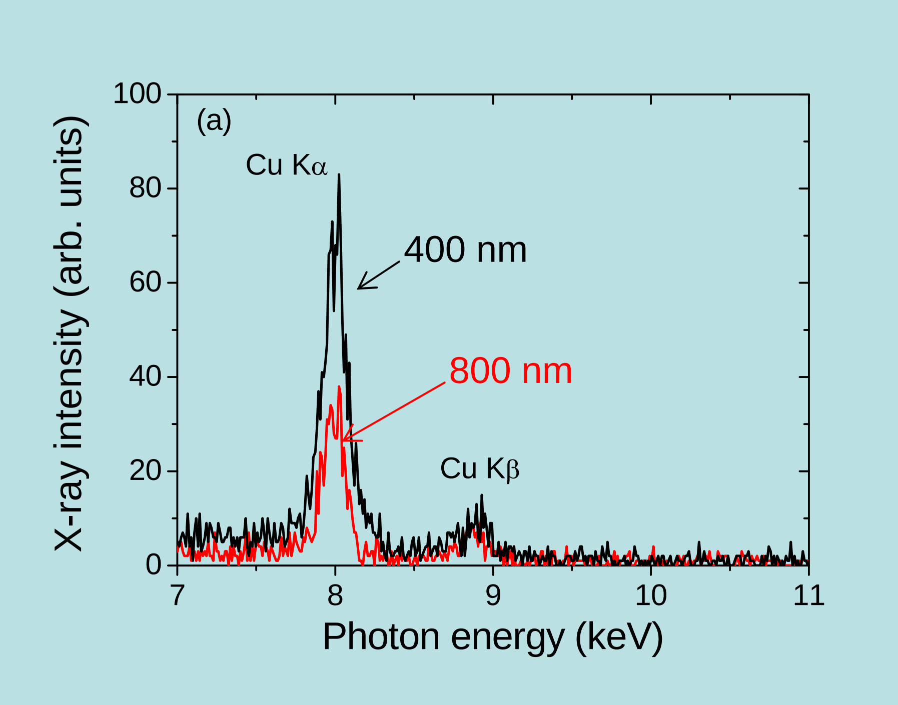
Smaller source size


Temporal profile of laser pulse

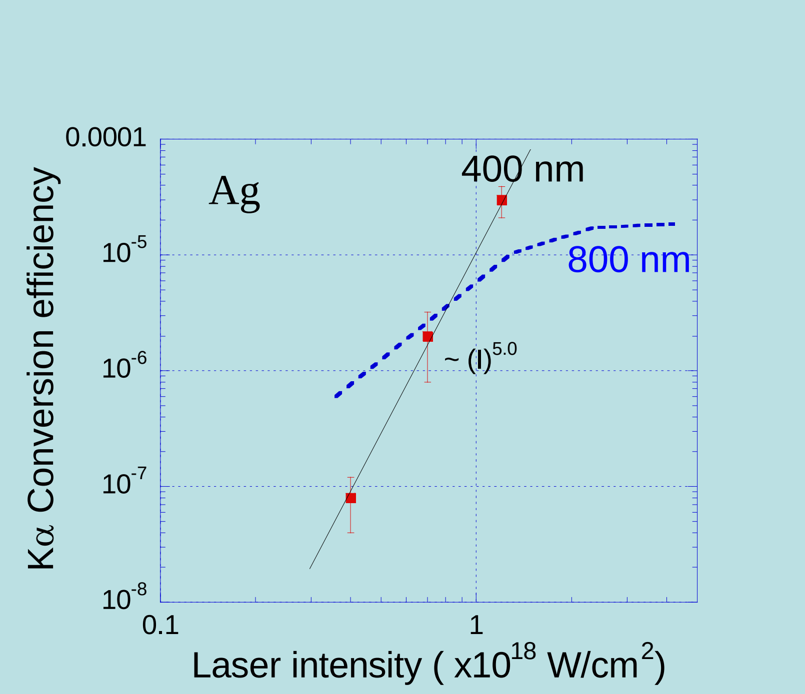
	800 nm	400 nm
Laser contrast ns	6x10^{4}	>10^{10}
Laser contrast ps	1x10^{4}	>10^{8}
Density gradient length (λ)	>3	<0.1
KT$_h$ (keV)	>150	~30
X-ray size (μm)	~100	~15

Effect of laser contrast (*I~1x10^{18} W/cm^{2}*)

Overcomes the saturation limit…



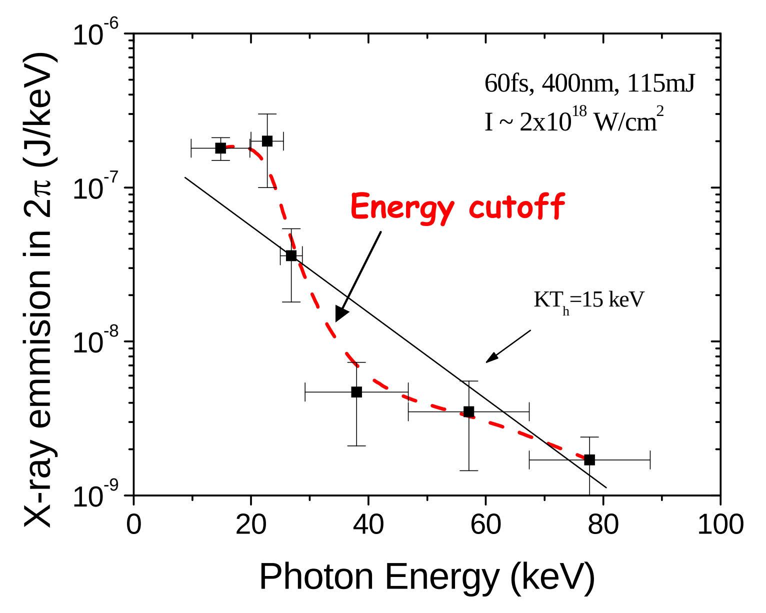
Comparison for kα photon emission
using 400 nm and 800 nm laser irradiation



Kα efficiency depend as a function of
laser intensity

- ➢High contrast fs laser is more effective for Kα photon generation
- ➢Kα efficiency does not show saturation at relativistic laser intensity using 400nm laser

Source contrast optimization…

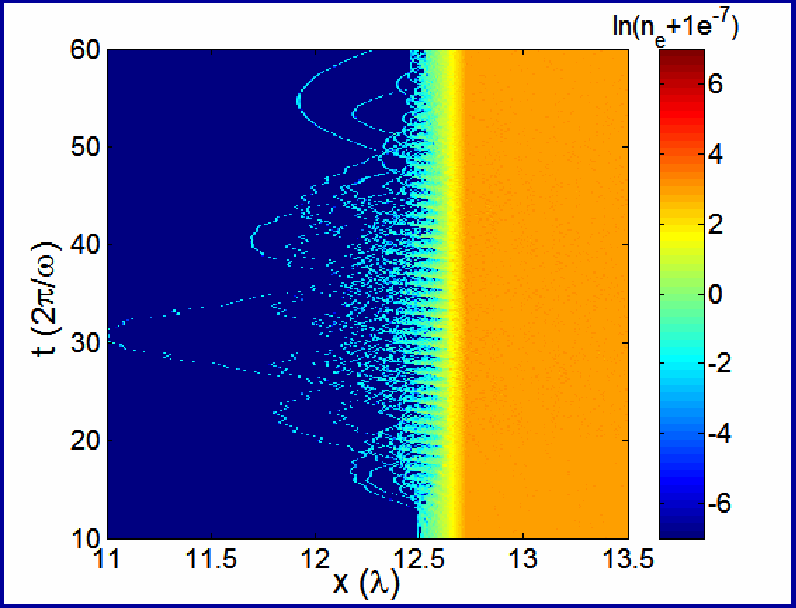


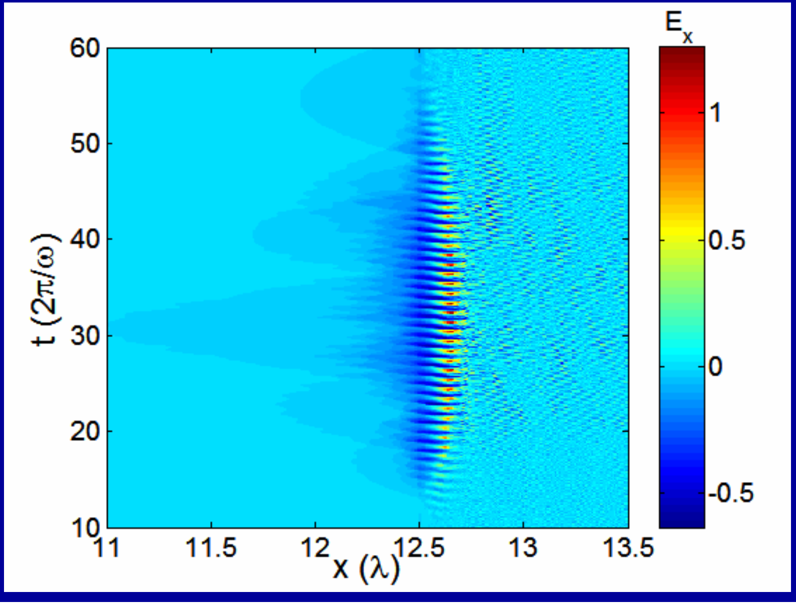
X-ray spectrum obtained under
400 nm laser irradiation

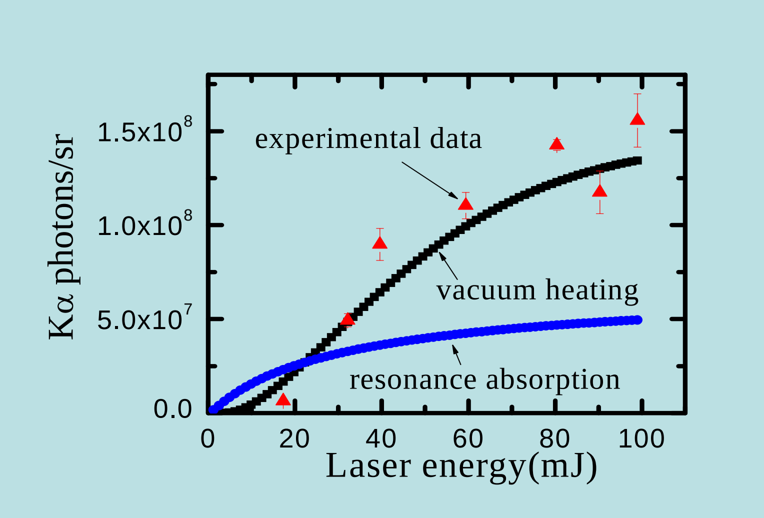
- The energy cutoff show in x-ray spectrum of high contrast laser
  ----energetic x-ray tail suppressed

Simulation with LPIC++

Vacuum Heating may be important mechanism







Calculation based on VH is more suitable for experiment than using RA

- *Electron quiver amplitude: $X_{osc}/\lambda > L/\lambda$*
- *Energy cutoff (~ 20 keV) ⇨ prove VH*

quiver energy: $E_q=eE_LX_{osc}$ =15 keV

⇨ expel JxB, RA (~100 keV)

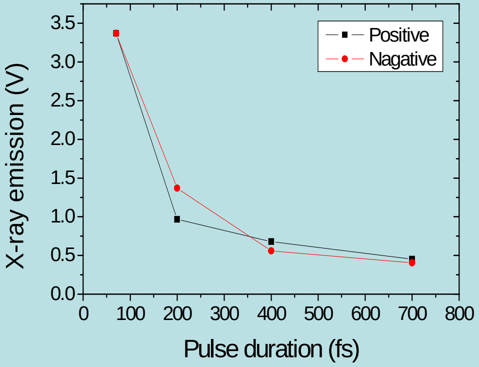
skin depth: $l_s \sim 10\ v_{th}/\nu$, where $v_{th}=(2kT/m)^{1/2}$

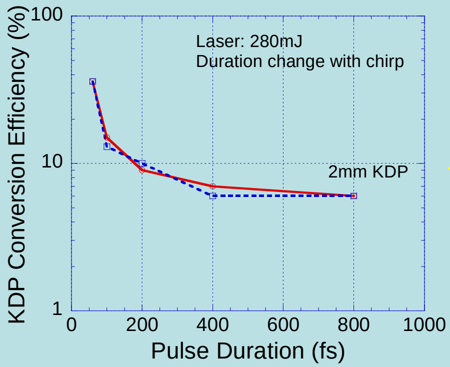
⇨expel SIB, ASE, STA ($l_s << v_{th}/\nu$)

➤VH stimulated using high contrast laser

Control of hard x-ray flux via laser pulse shaping

Low contrast laser

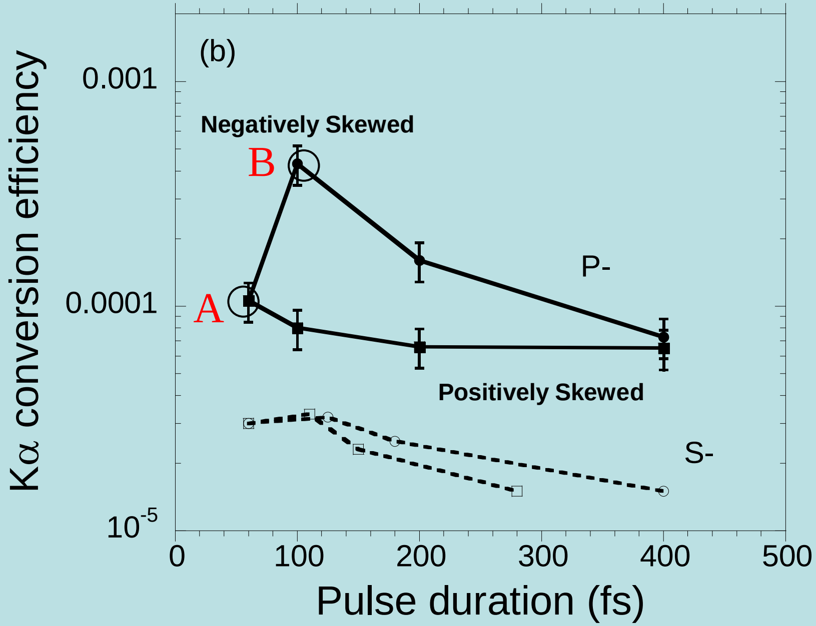




KDP conversion efficiency vs. pulse duration under different pulse shape

---To get the right grating zero

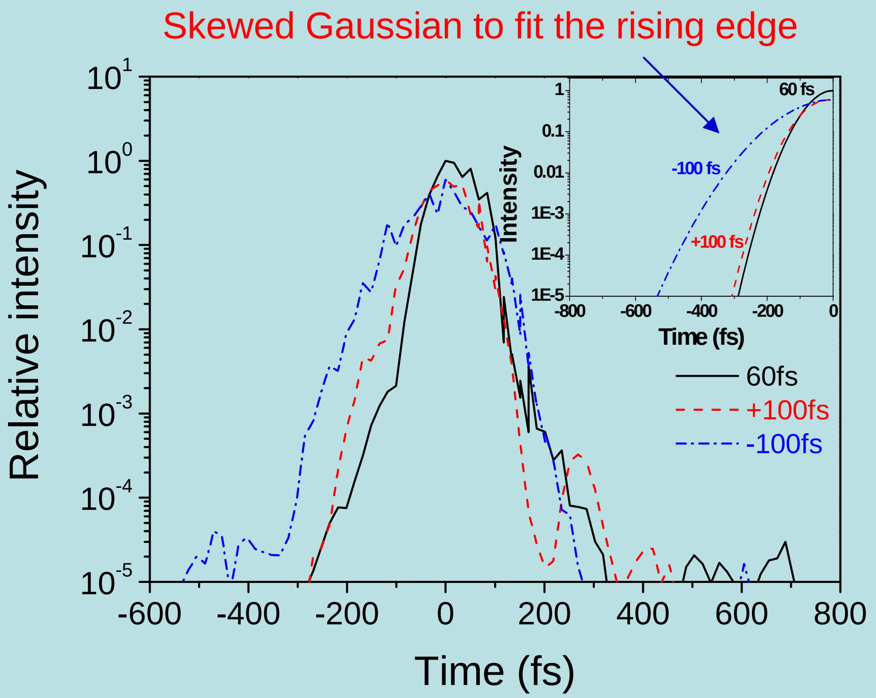
High contrast laser



Kα conversion efficiency vs. pulse duration in differently skewed pulse shape

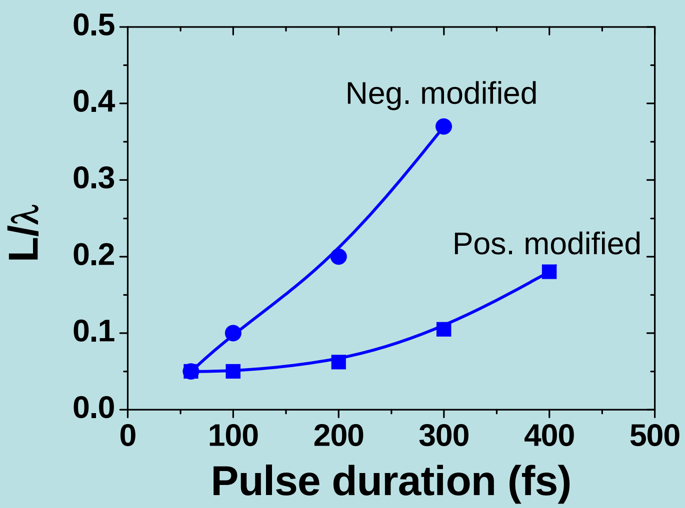
- ➢ η_K show significant chirp dependence
- ➢ The maximal η_K ~ *4x10^{-4}, Similar to theoretical calculation limit.*

Control of x-ray emission via laser pulse shaping


Skewed Gaussian to fit the rising edge

Temporal profile in different pulse duration/chirp

Calculation using HYADES



Plasma scale length in various pulse width and constant pulse energy

(laser intensity 1x10^{18} W/cm^2 on 60 fs)

L(-100fs)=0.1λ (optimal for VH)

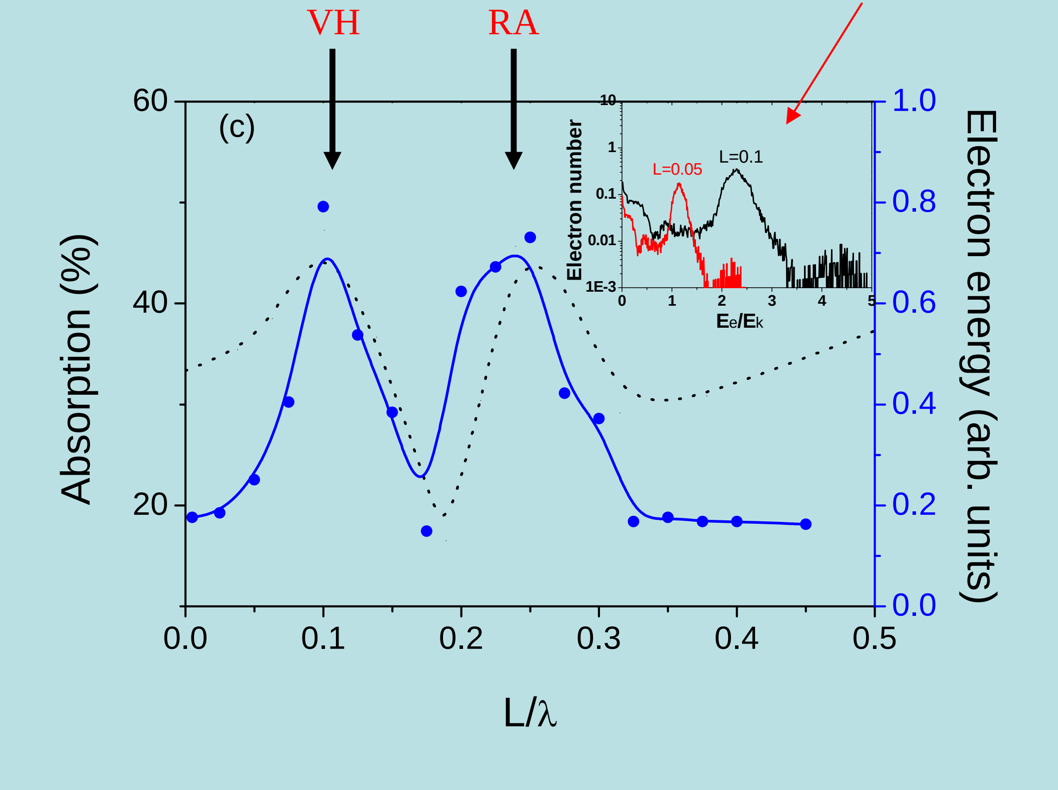
L(+100fs)=L(60fs)=0.05λ

The pre-plasma scale length can be controlled by the rising edge of high contrast laser pulse

Simulation with LPIC++

Control of x-ray emission via pre-plasma

The peaked electron spectrum driven by high contrast laser

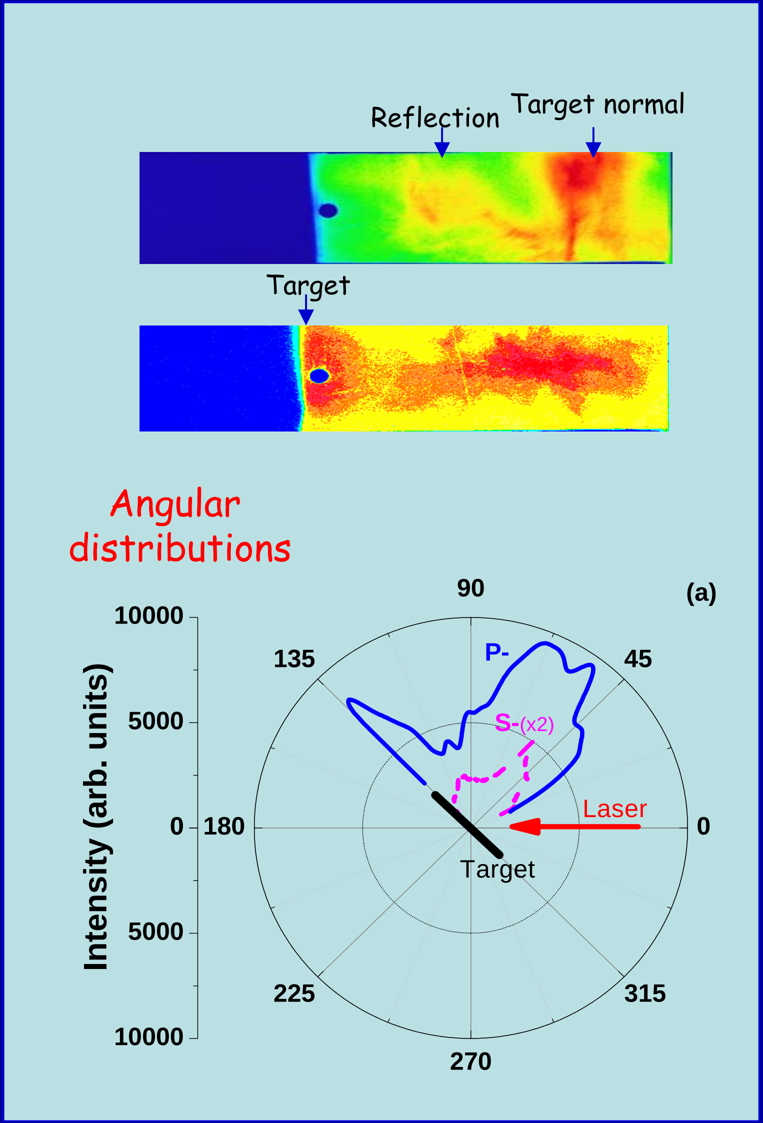


Integrated electron energy/absorption vs. density gradient

P-polarized laser with 30 optical cycles
at 1x10^{18} W/cm^2 incident on target at 45^0

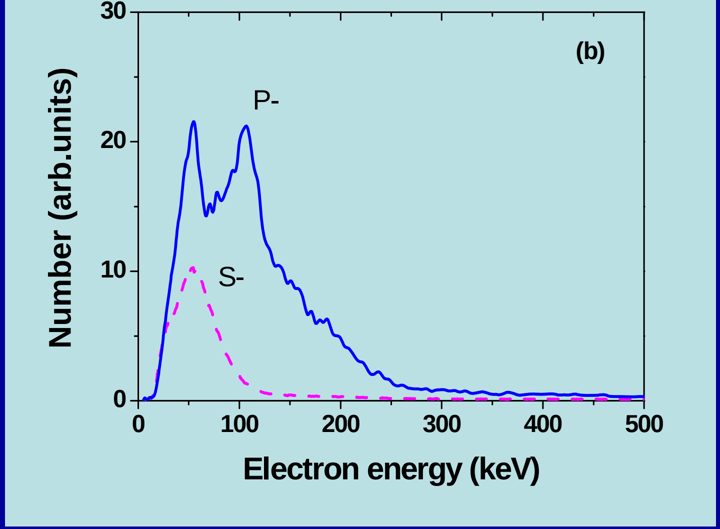
- The level of VH stimulation is critically depend on L
- Preciously control of VH is possible via tuning the high contrast laser rising edge

Polarization dependence of hot electron generation



- Electron show wider angular distribution along target normal. (evident of VH)
- Distinct target surface emission (P-pol.)
- Electron spectrum peaked.
- The second electron group appears (P-pol.) in spectrum, shows monoenergetic structure.

Spectra obtained in 125^0



L. M. Chen et al, Phys. Rev. Lett. 100, 045004(2008)

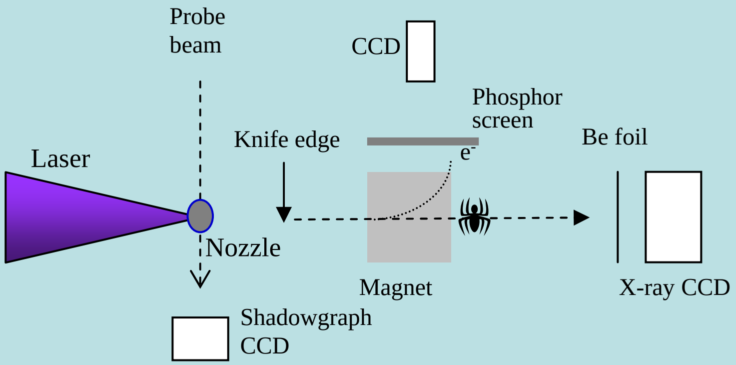
need more pure source
for imaging?

K-shell keV Ar X-ray source Using TW laser

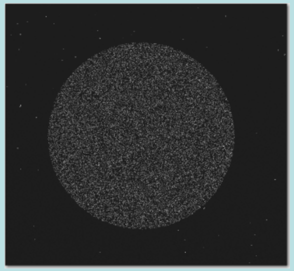
(Laser contrast 10^8)

High contrast Ar K-shell keV source

Experimental setup

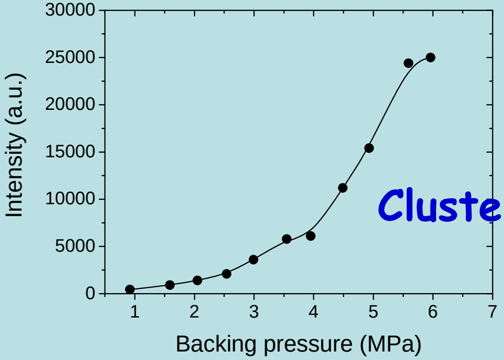


Source imaging on CCD



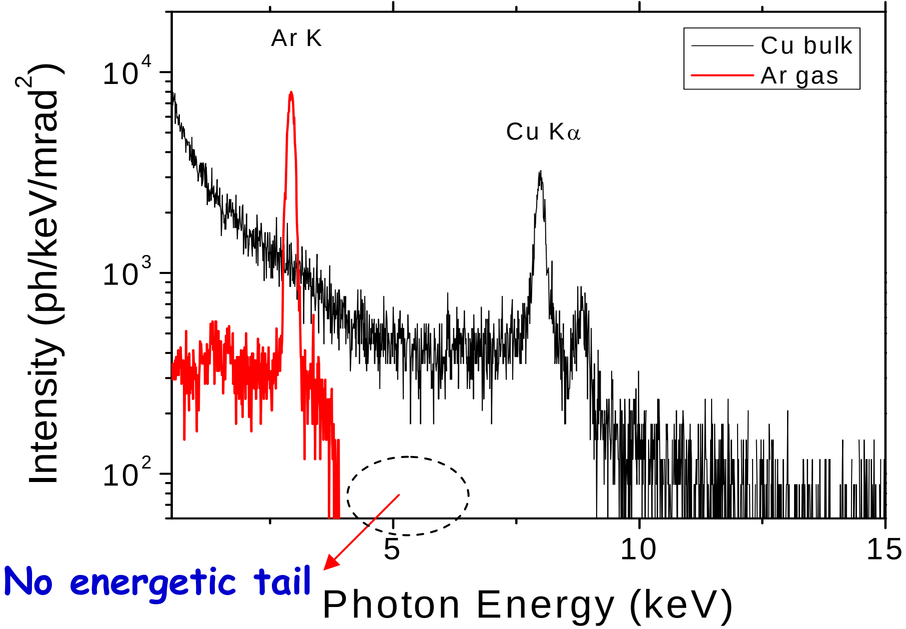
Pure, clear

Rayleigh scattering measurement



Cluster formed

X-ray spectrum



No energetic tail

High contrast: peak/bkgd>20

E_K/E_{total}>70%

Quasi-monochromatic

Intense: B=10^{20} phs/s/mm²/mrad²

Coherent (small size=12 μm)

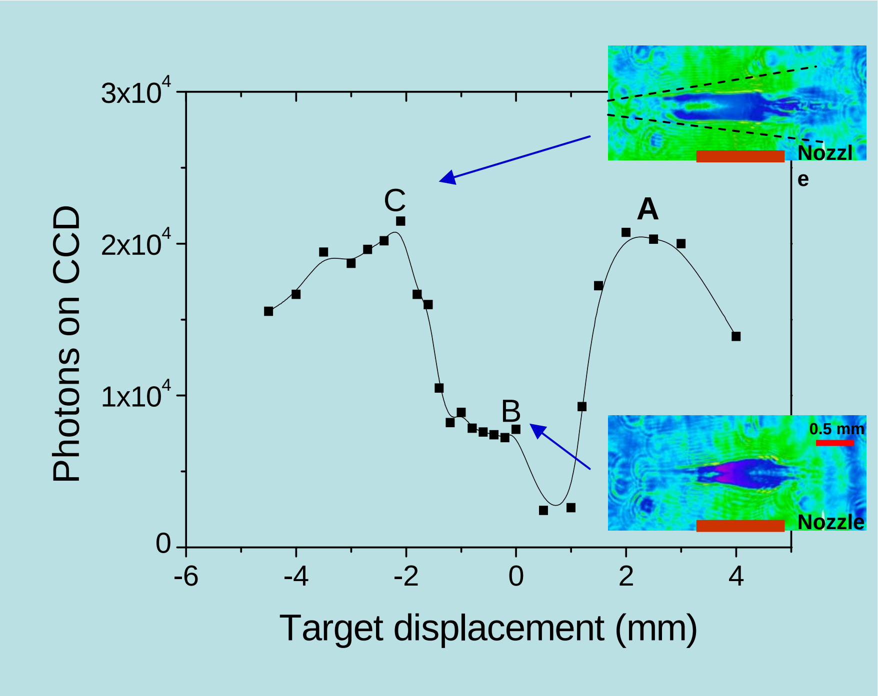
Directional: $I_{Long.}/I_{Trans.}$>10

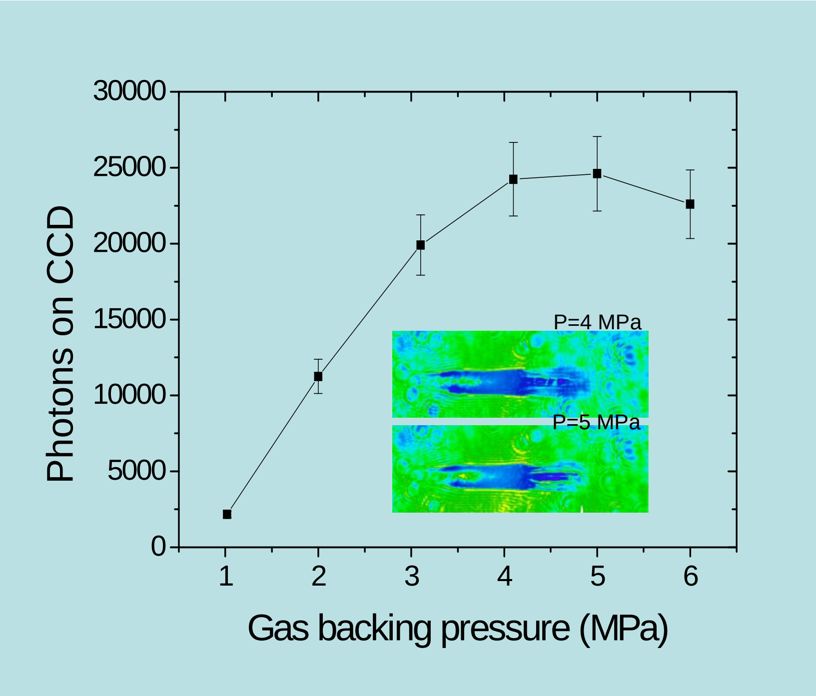
- Continuum background

  $\Sigma N_{K\alpha}/\Sigma N_{xray}$ ~ 10%

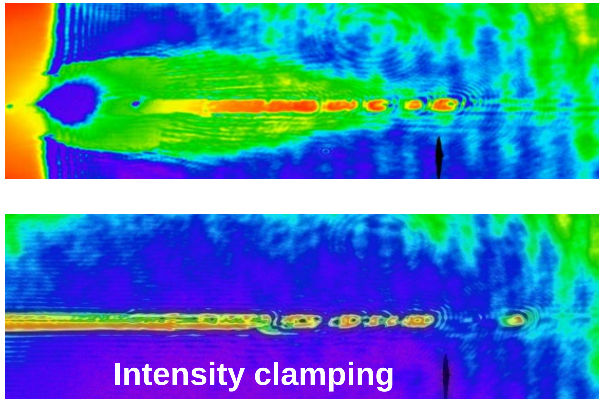
  --polychromatic

Source optimization…



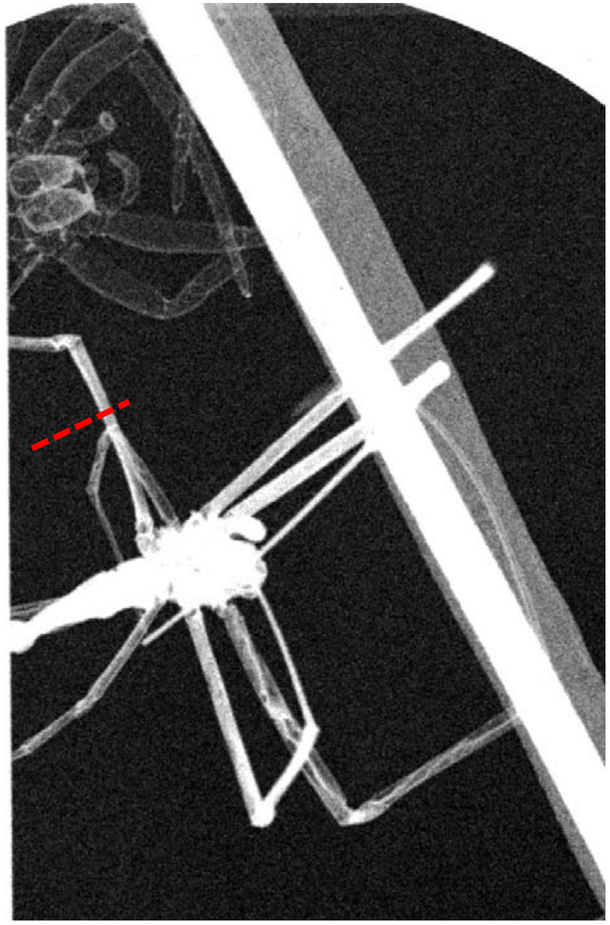


Long guiding **(box 1.4x0.4 mm)**

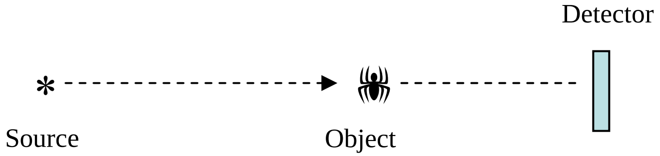


- Source flux enhanced when long channel formed

Phase-Contrast imaging

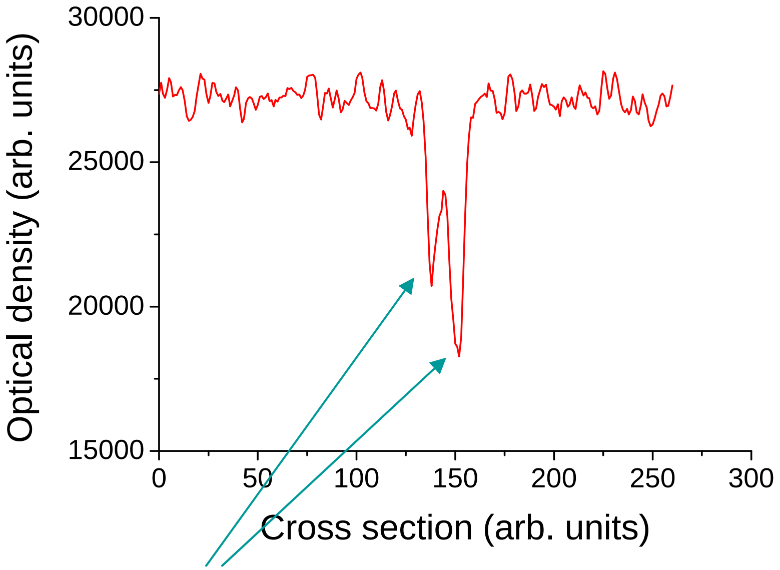


Sharp imaging…



SOD=38.5 cm
SDD=132 cm

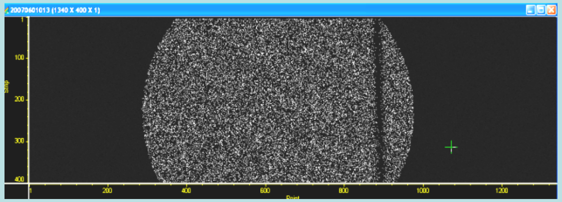
Photon density on IP
~ 5 x 10^6 /cm^2

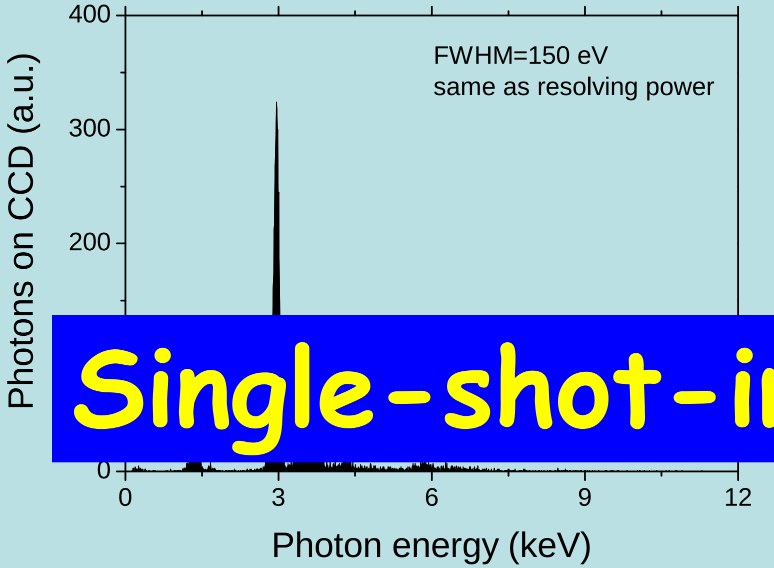


Imaging edge greatly enhanced

New progress…

Imaging on CCD





Comparison … **Ar keV flux x10 !!**

	Jlite-X	**J-Karen**
E_L(mJ)	200	800
τ (fs)	70	28
Contrast (to ps ASE)	10^6	$>10^9$ (adjustable)
I_{peak} (W/cm^2)	4×10^{17}	8×10^{18}
Kα flux (phs/mrad^2)	**1.2×10^3**	**1.1×10^4**
(phs/s/mm^2/mrad^2)		

Single-shot-imaging available !!

Photon flux on IP:5×10^6 phs/cm^2

Summary…

- The laser based hard x-ray source is optimized by using high contrast pulse:
  - **Enhanced and controllable x-ray yield; Smaller x-ray source size**
  - **Suppressed energetic x-ray tail and energy cutoff**
  - **X-ray emission in shorter time scale (assumed)**
  - **Quasi-monoenergetic with low background**

- In the field of *fs* laser physics, VH would be the main mechanism for hot electron generation. Precisely control the level of VH stimulation succeed via tuning the high contrast laser rising edge

- Extremely strong Ar K-shell x-ray source is archived. High contrast laser is the right choice to generate this source

Optimized x-ray source may allow imaging with…

- Improved specificity----higher contrast and higher spatial resolution
- Improved sensitivity----lower detection threshold
- Reduced dose on sample----better figure of merit (FOM)

Thank you