Extending the Capabilities of Ablation Harmonics to Shorter Wavelengths and Higher Intensity

T. Ozaki, L. Elouga Bom, R. A. Ganeev, J.-C. Kieffer
INRS - EMT, Univ. Québec

Proceedings of the 3rd International Conference on the Frontiers of Plasma Physics and Technology (PC/5099)

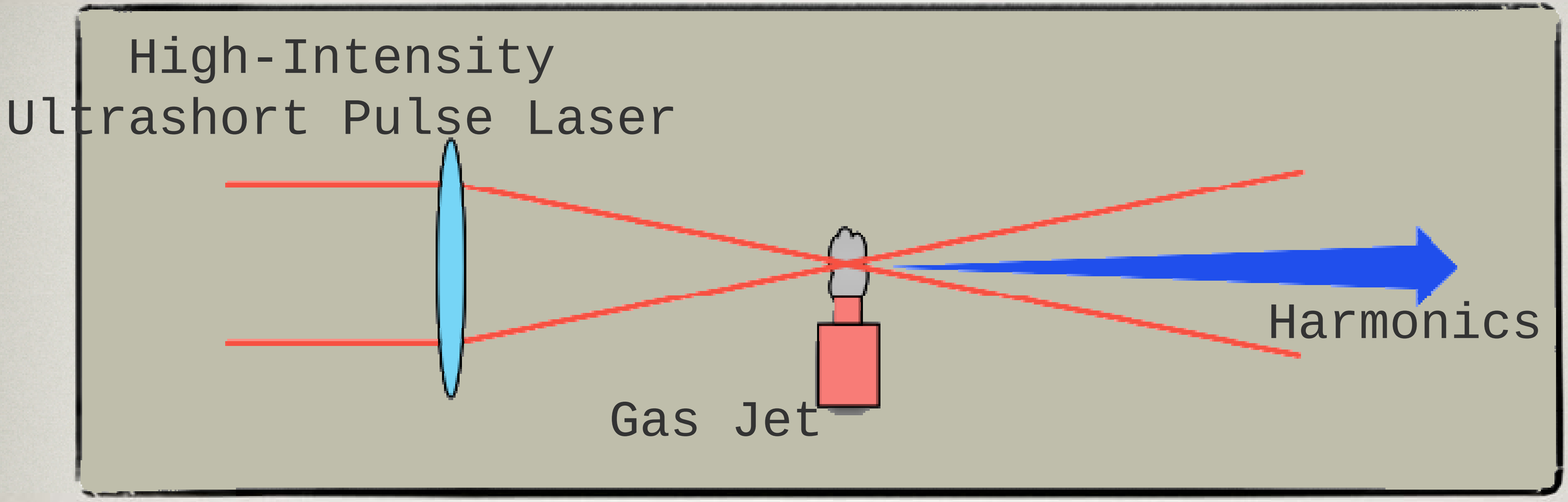
S2-4

Université du Québec
Institut national de la recherche scientifique

Outline

- Ablation Harmonics: A highly efficient method for harmonic generation
- Silver Harmonics: Intense sources in the plateau
- Quasi-monochromatic, intense harmonics using indium and tin ablation
- Manganese Harmonics: Extending harmonics to shorter wavelengths

Université du Québec
Institut national de la recherche scientifique



High-Order Harmonics

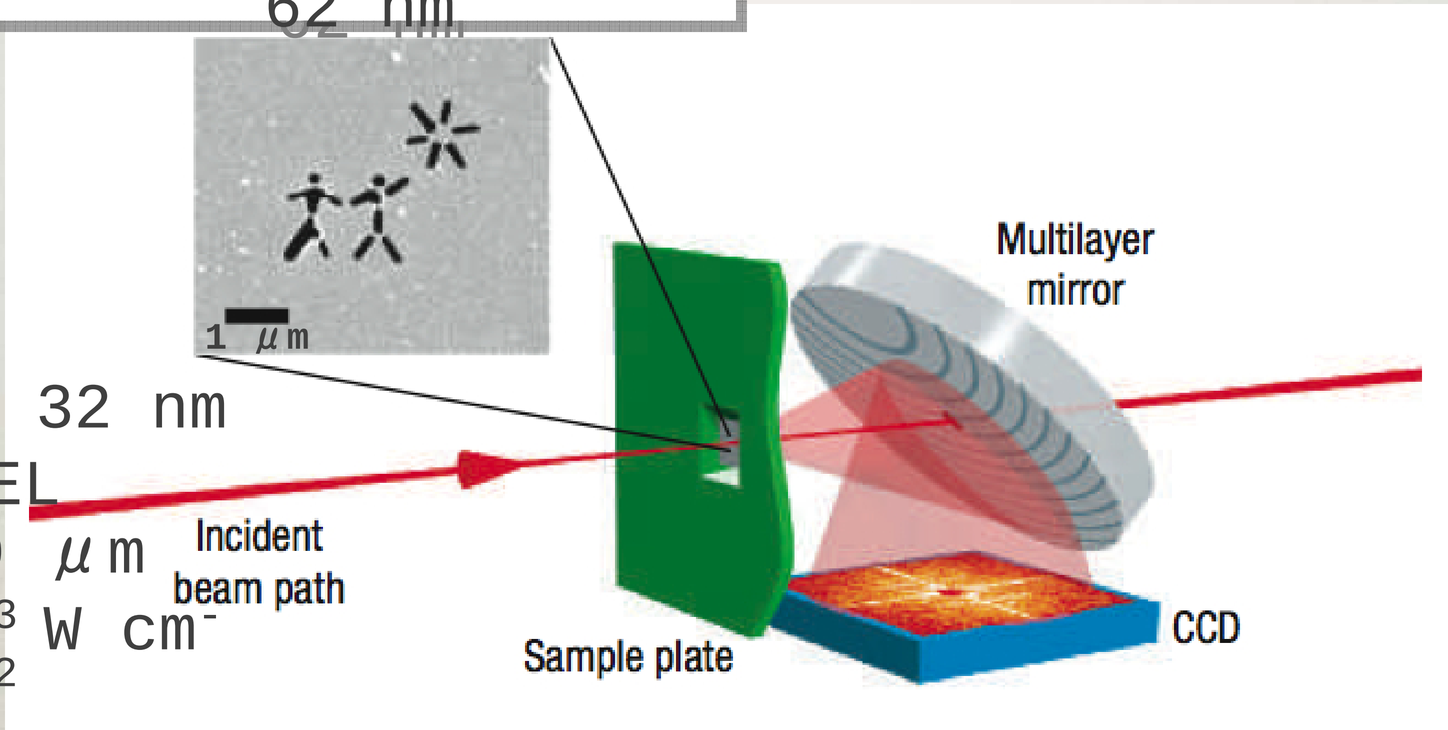
- Coherent soft x-ray beams (odd multiple orders of pump)
- Low-divergence (~ mrad)
- Ultrashort pulse (femtosecond, and even attosecond)
- Harmonic orders > 500, photon energy > 1000 eV, observed

☑ Low conversio … $^{-6}$ to 10^{-7})

Femtosecond diffractive imaging with a soft-X-ray free-electron laser

Chapman et al., *Nature Physics* **2**, 839 (2006)

Spatial resolution: 62 nm



6 μJ, 32 nm FEL

Φ20 μm

4×10^{13} W cm^{-2}

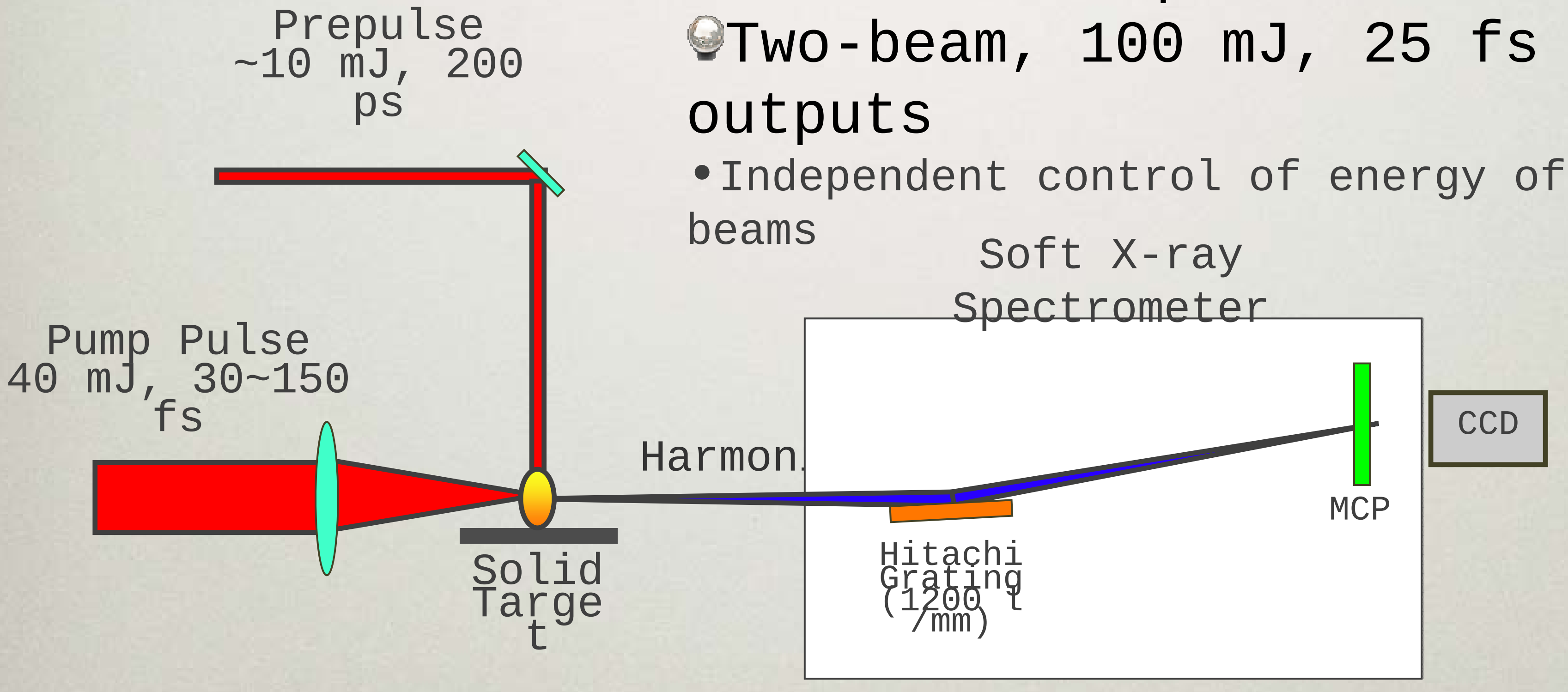
Ablation Harmonics

A New Method to Generate Intense Harmonics

The Idea ... use dense laser-ablation media as the nonlinear medium

Setup at ALLS

- Two-beam, 100 mJ, 25 fs outputs
  - Independent control of energy of the two beams

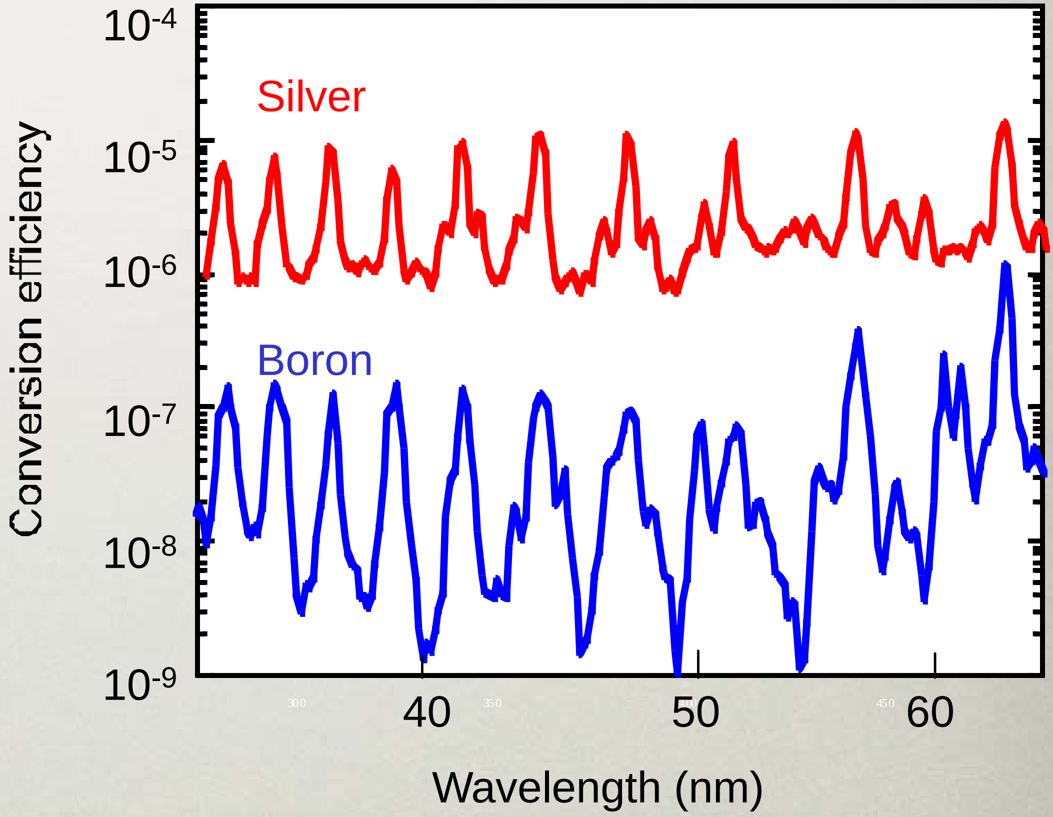


Université du Québec
Institut national de la recherche scientifique

Ablation Harmonics are Highly Efficient

- High conversion efficiency of 10^{-5} demonstrated in the plateau (13^{th} ~ 31^{st})

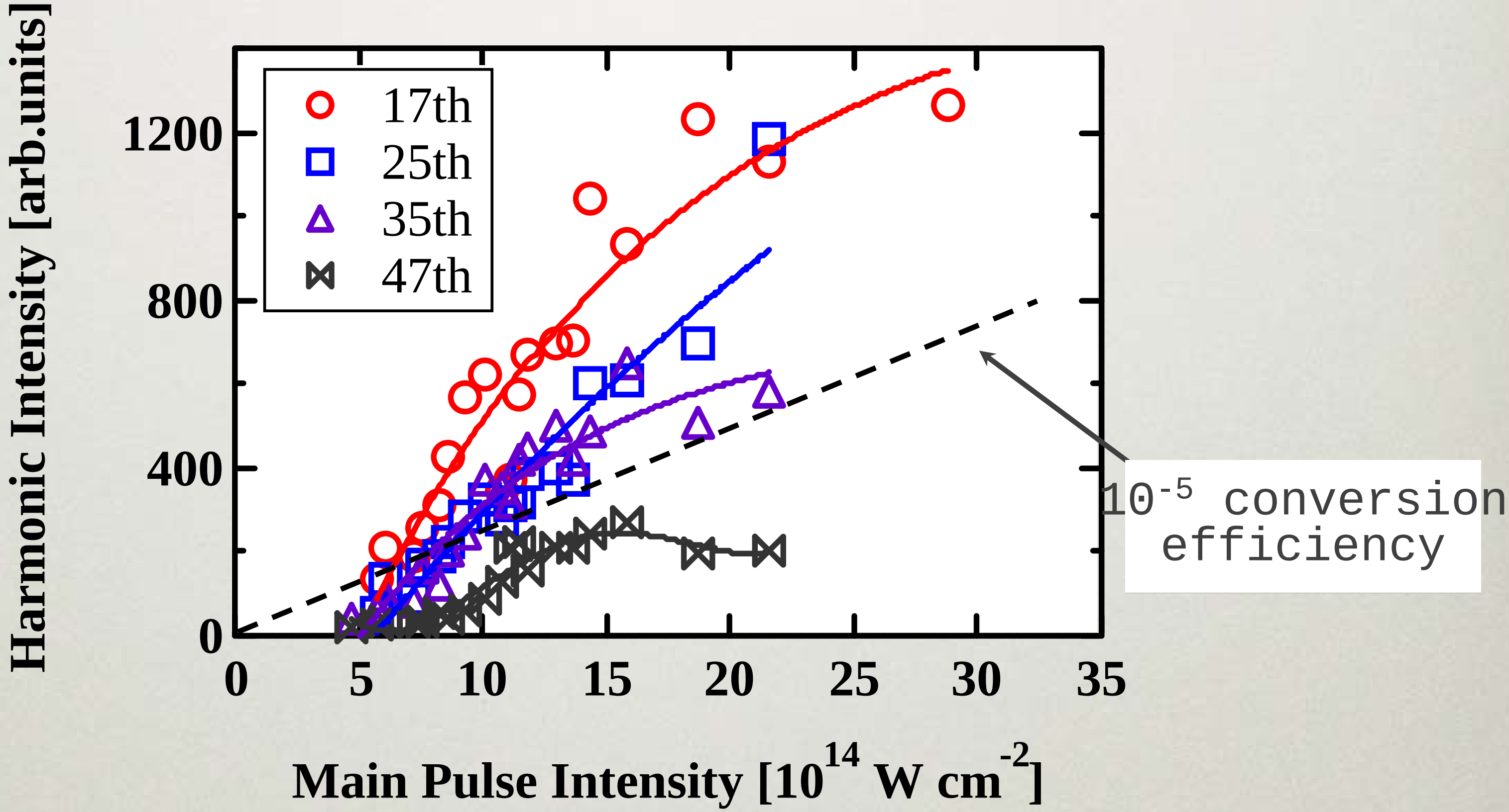
(Silver)



- Sub-μJ harmonics already obtained with 10 mJ pump
  - Multi- μJ harmonics envisaged with full use of ALLS 150 mJ pump

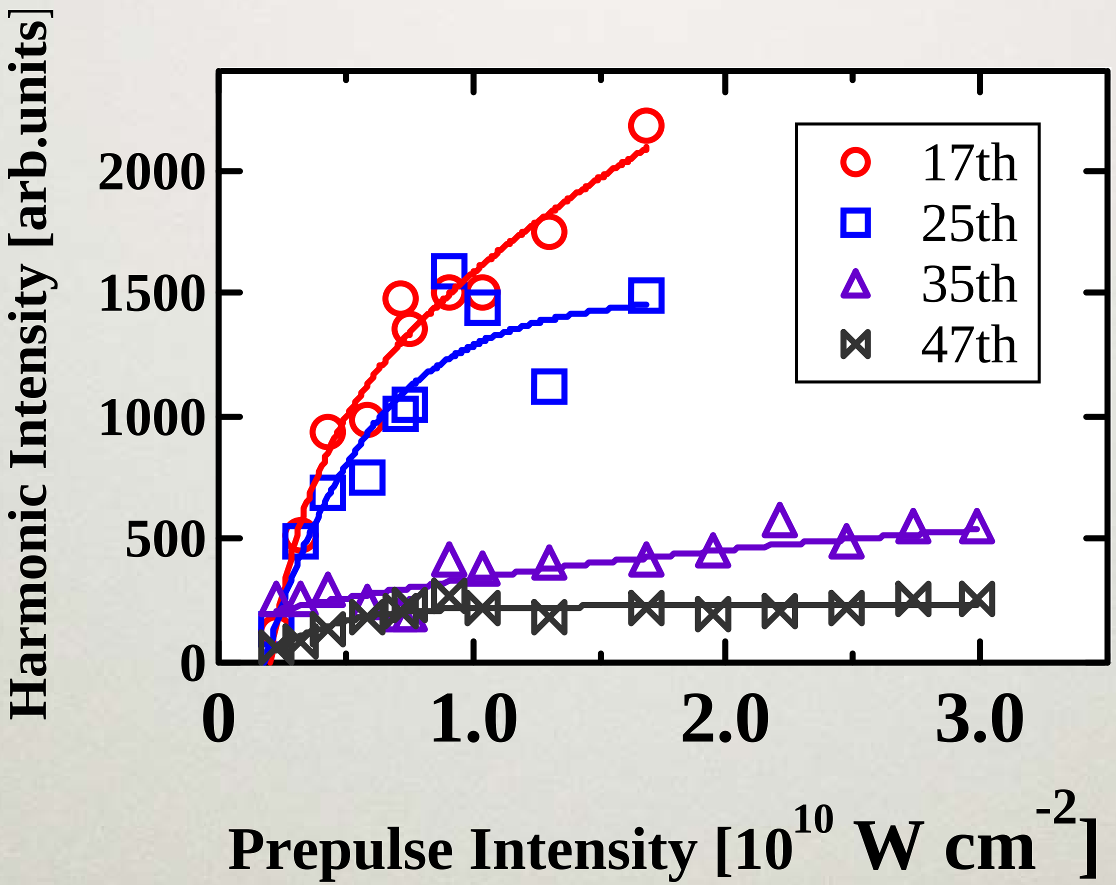
Université du Québec
Institut national de la recherche scientifique

Ag Ablation Harmonic Intensity as a function of Main Pump Intensity



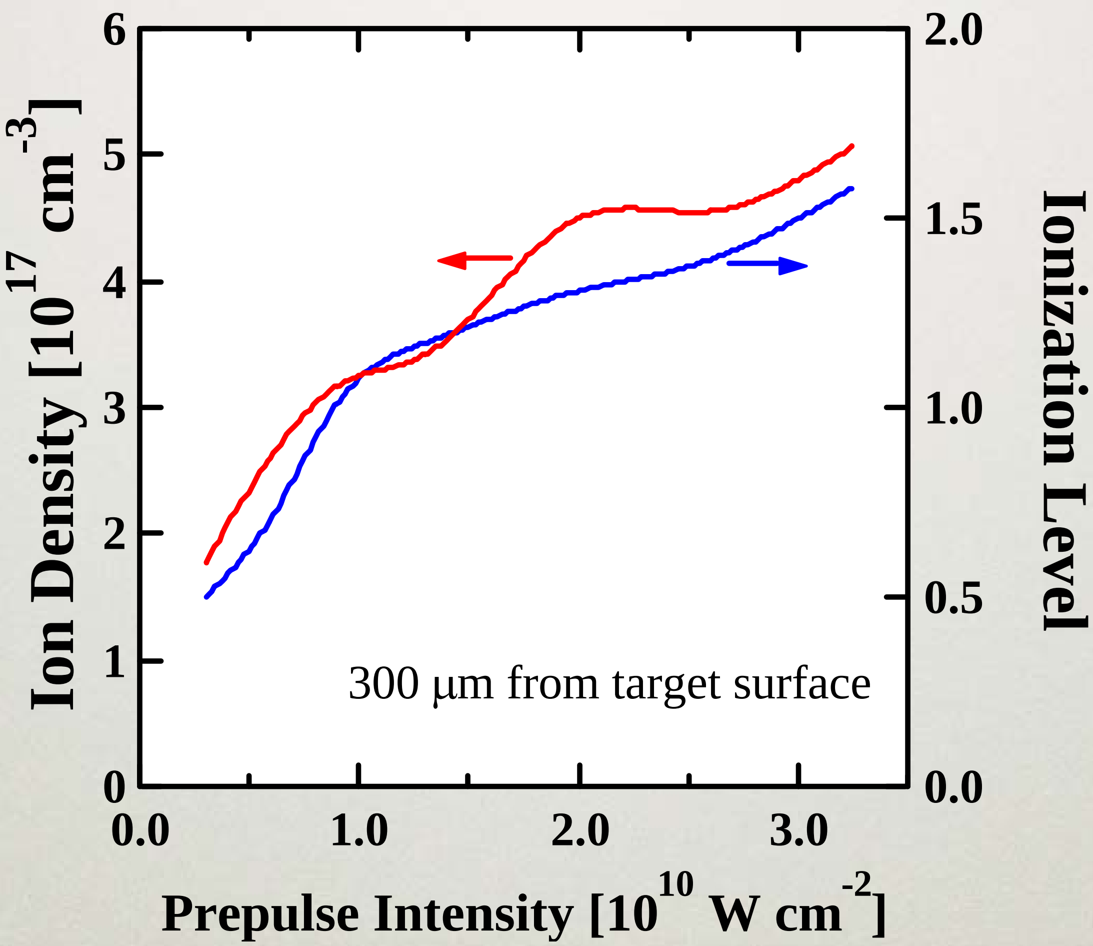
Université du Québec
Institut national de la recherche scientifique

Prepulse Intensity has large effects on Ablation Harmonics



Université du Québec
Institut national de la recherche scientifique

Higher Prepulse Intensity results in Higher Ion Density

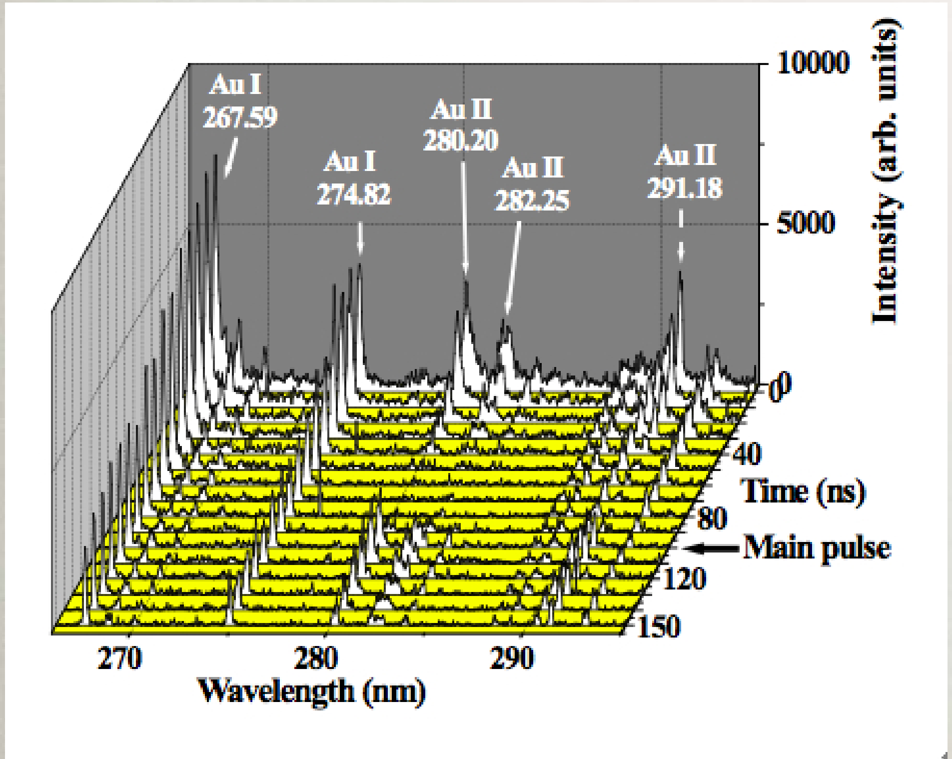


Université du Québec
Institut national de la recherche scientifique

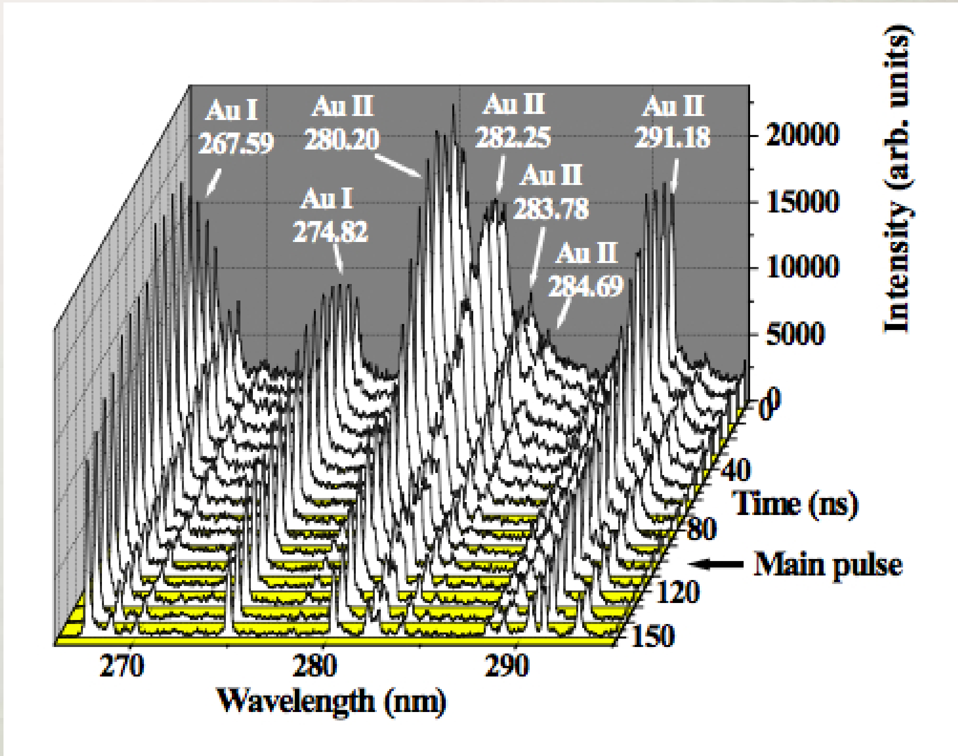
to be Controlled Carefully

Gold Harmonics

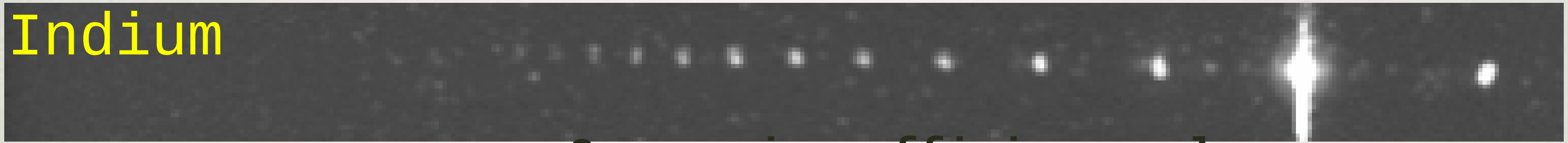
HHG Positive



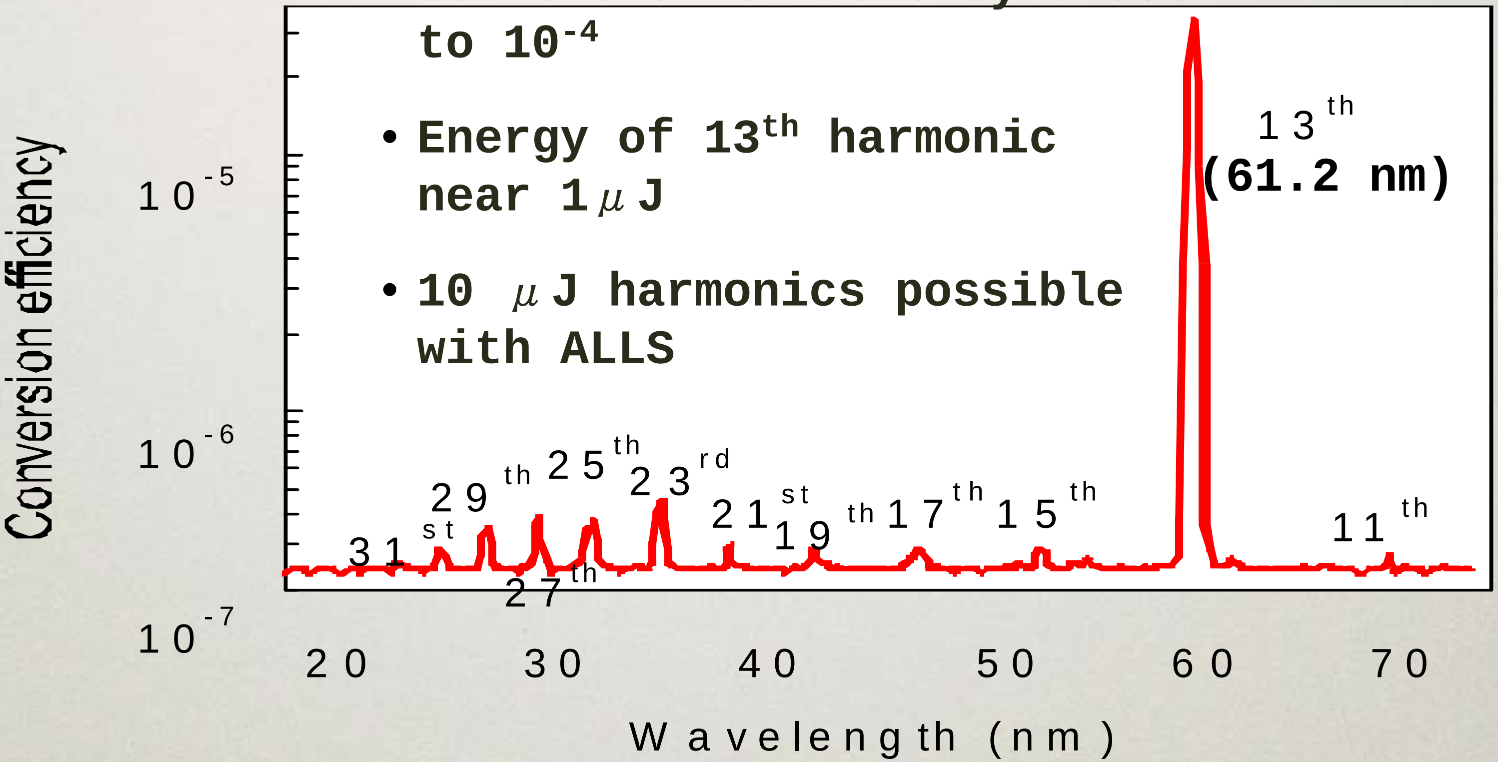
HHG Negative



Intense Quasi-monochromatic Harmonics from Indium Ablation



- Conversion efficiency close to 10^{-4}
- Energy of 13th harmonic near 1 μJ
- 10 μJ harmonics possible with ALLS



ll harmonics disappear with elliptical polarization pum

Université du Québec
Institut national de la recherche scientifique

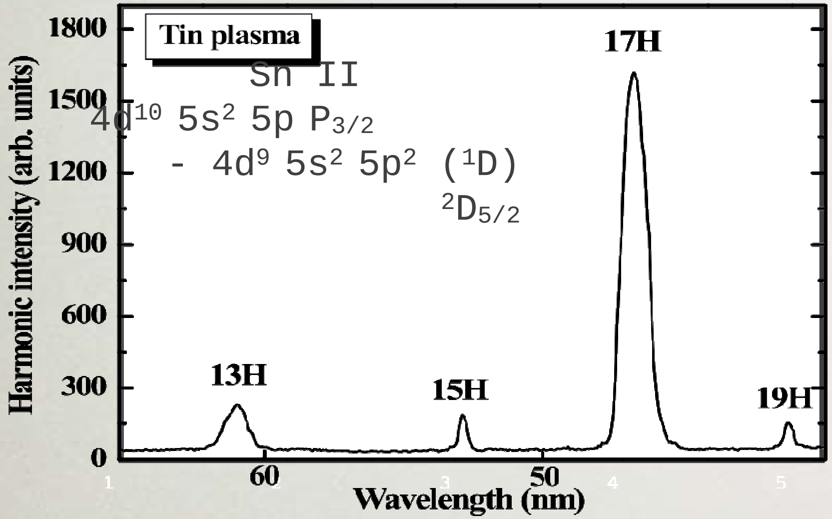
Other Quasi-Monochromatic Harmonics

1) Tin (Sn)

Intense 17 H, λ=47.05 nm

Sn II

$4d^{10}\,5s^2\,5p\;P_{3/2}$ - $4d^9\,5s^2\,5p^2\;(^1D)\;^2D_{5/2}$

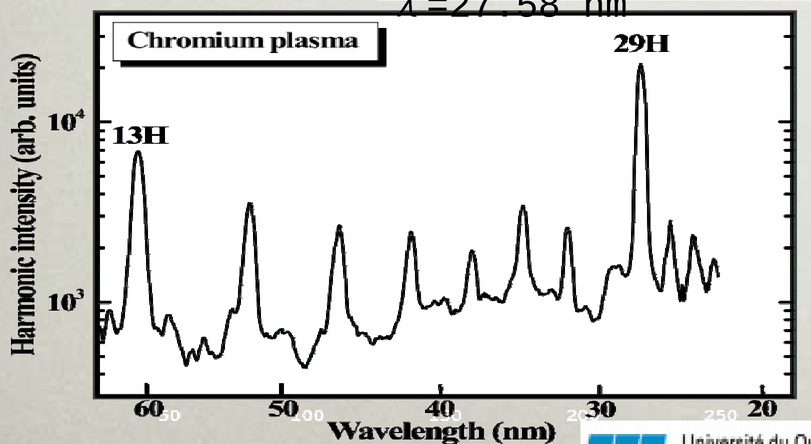


800 nm pump

400 nm pump

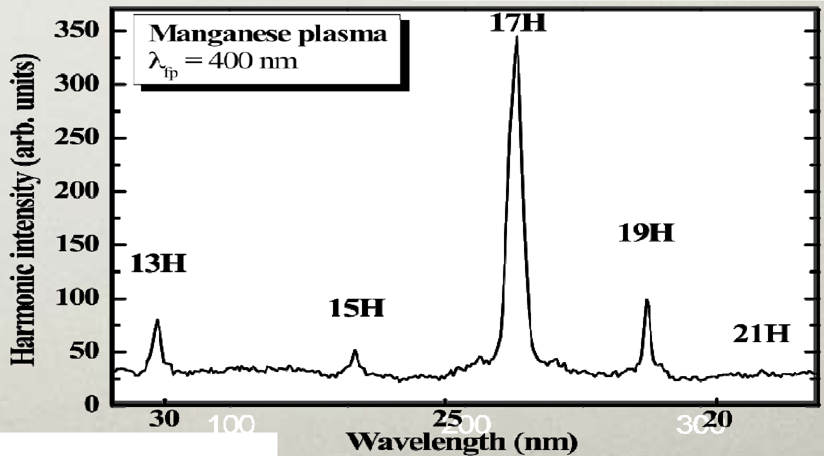
2) Chromiun (Cr)

Intense 29 H, λ=27.58 nm



3) Manganese (Mn)

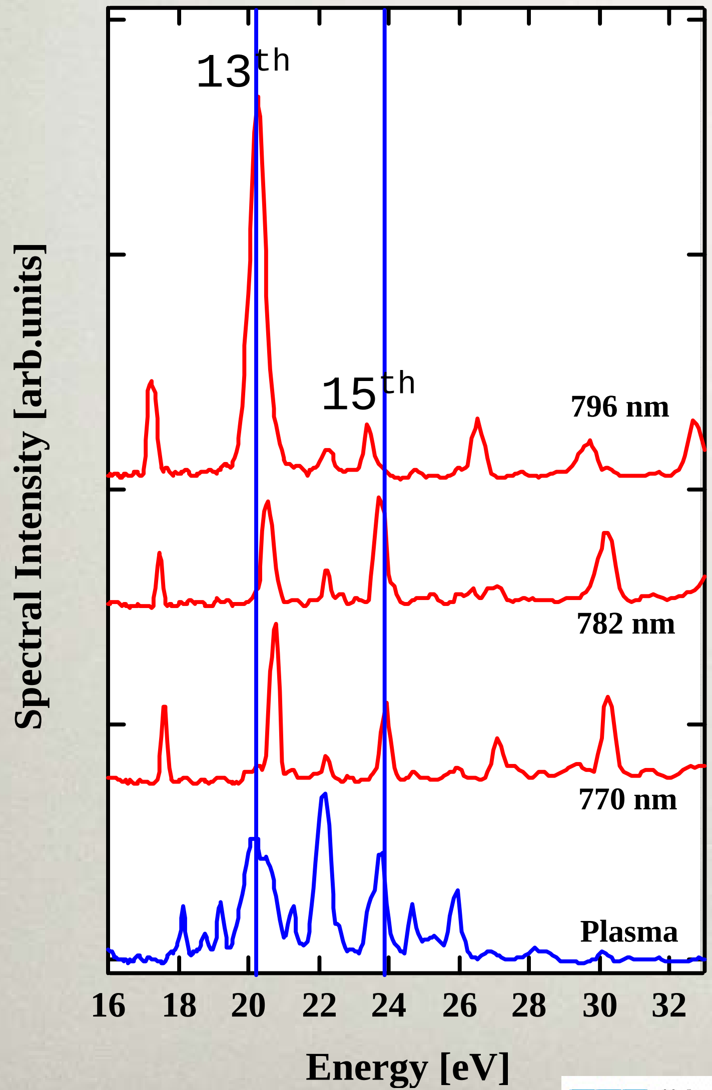
Intense 17 H, λ=23.5 nm



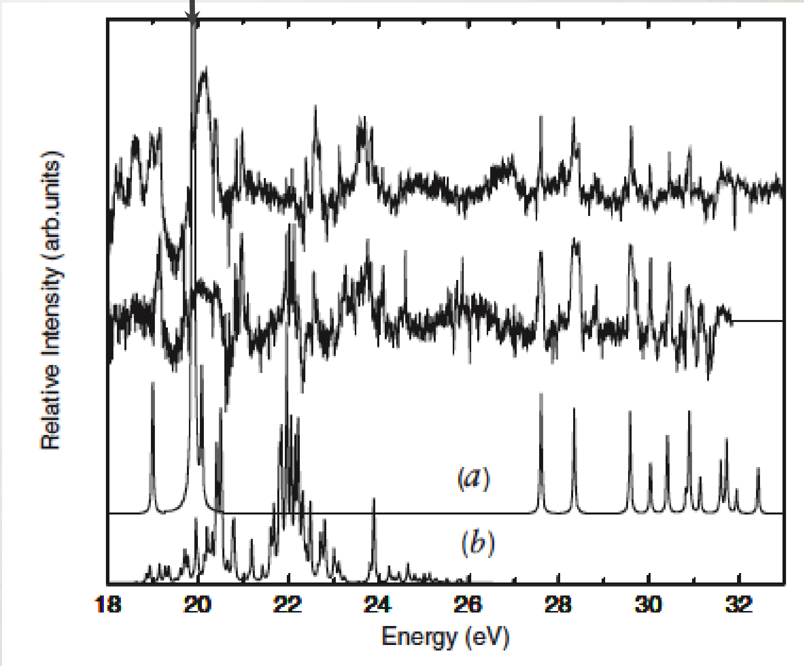
Université du Québec

Institut national de la recherche scientifique

Comparison of Harmonic Spectra with Emission from Over-ionized Plasma



$4d^{10}5s^2\ ^1S_0 \rightarrow 4d^95s^25p(^2D)\ ^1P_2$
(19.92 eV) : *gf* = 1.11



Calculated synthetic spectra to (a) In II $5s^2$ ground state, and (b) In II 5s5p state

Ref.: G. Duffy & P. Dunne, J. Phys. B 34, L173 (2001)

Université du Québec
Institut national de la recherche scientifique

Improved Phase Matching due to Anomalous Dispersion

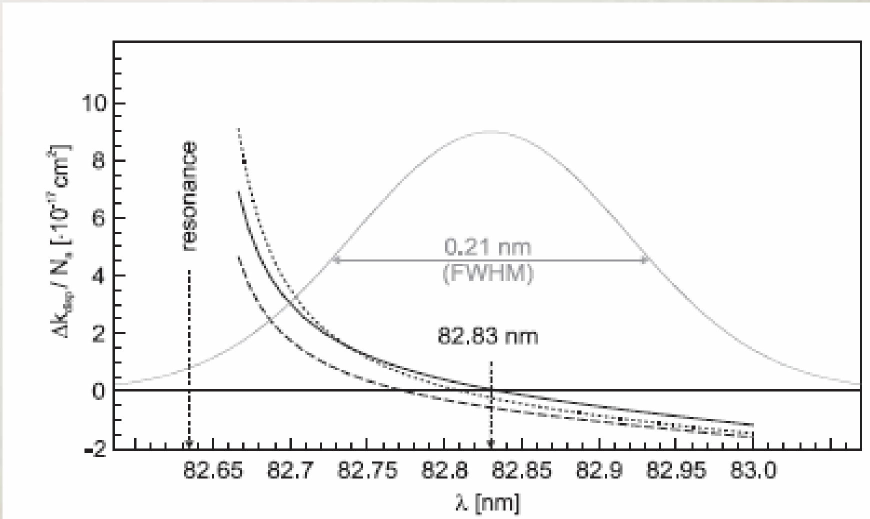
Phase-matching condition for q^{th} harmonic

$$\Delta k \approx N_e r_e (q\lambda_\omega - \lambda_{q\omega}) - \frac{2\pi N_a}{\lambda_{q\omega}}\left[\delta(\lambda_\omega) - \delta(\lambda_{q\omega})\right]$$

$N_{e(a)}$: electron (atom) density; r_e: classical electron radius; $\lambda_{q\omega}$: wavelength of q^{th} harmonic; δ: neutral atom dispersion

Idea: use anomalous dispersion near strong resonances to compensate for increased phase mis-match due to N_e

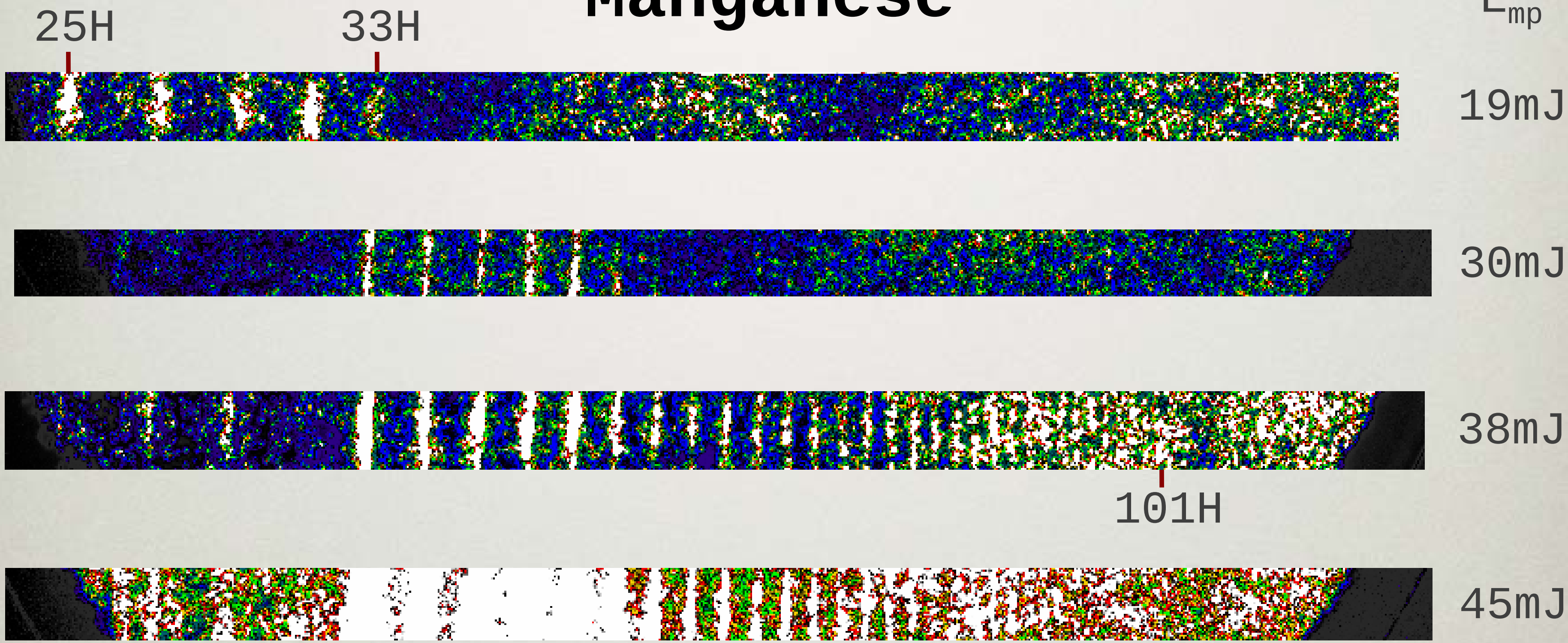
... already demonstrated for third harmonic of KrF laser in Ar



C. Dölle *et al.*, *Appl. Phys. B* **75**, 628-634

Going to Shorter Wavelengths

Extending the Cut-off with Manganese



- Largest cut-off (101^{th} order, λ = 7.9nm) ever observed with this method
- Two plateaus

Université du Québec
Institut national de la recherche scientifique

What makes Manganese Different ?

I_p	1^{st} [eV]	2^{nd} [eV]	3^{rd} [eV]
Mn	7.43	15.64	33.67
Au	9.22	20.52	30.05

Ionization potential
... not that different

Electron density of Ablation
(I_{pp} = 2 x10^{10} W/cm^2)
Simulated by HYADES

Mn: 3.25 x10^{17} cm^{-3}
Au: 14.2 x10^{17} cm^{-3}

Under the same prepulse condition, the electron density for Mn is unusually low

... reduced negative effects of free electrons

Conclusions

- Ablation harmonics: *Intense sources of high-order harmonic generation*
  - Silver harmonics: *intense sources in the plateau*
  - Quasi-monochromatic harmonics: *intense, single-line harmonics*
- Manganese harmonics: *One step toward shorter wavelength harmonics*
  - Low electron density of ablation medium

Université du Québec
Institut national de la recherche scientifique