Bright harmonic radiation from Argon Ions

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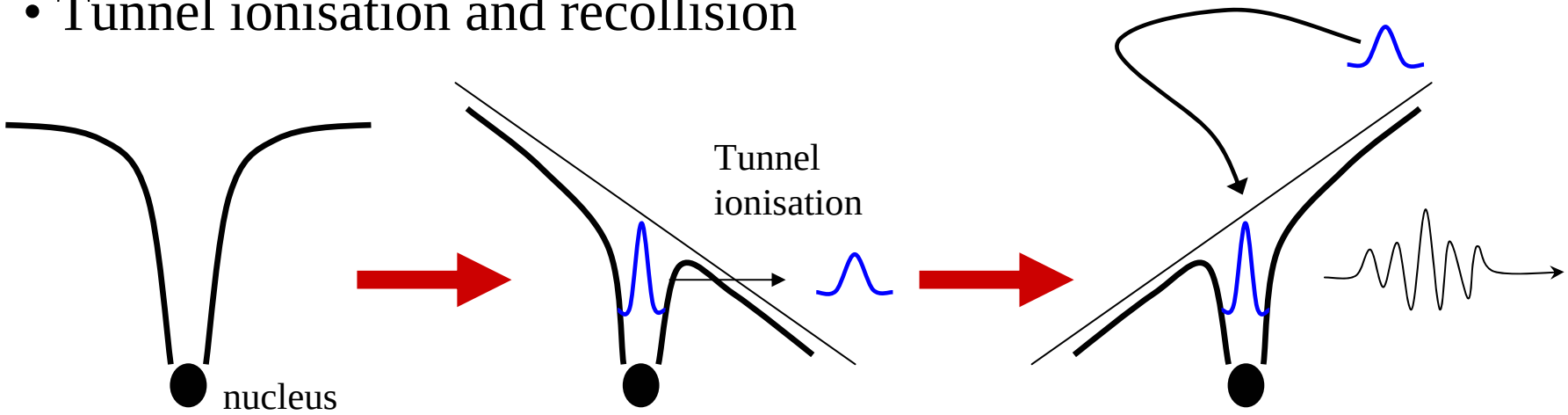
Outline

- Brief description of the underlying physics
  - Theory of HHG from laser gas interactions
  - Quasi Phase Matching of HHG from laser gas interactions
  - Propagation of intense laser pulses in hollow capillaries
- Experimental Setup and Multimode beating
- Results

High Harmonic Generation from gas targets

Strong Field Model

- Tunnel ionisation and recollision



Atomic Potential Well

Distortion due to E-field of laser

Electron acceleration in E-field of laser and recollision

- The electron is accelerated in the electric field of the laser
- Photon of energy $E = h\nu = I_p + 3.2\ U_p$ is emitted
- Only odd harmonics emitted: Symmetry

Phasematching HHG from Gases

$$L_c = \frac{\pi}{|\Delta k|}, \quad \Delta k = k_q - q k_0$$

where L_c is called the coherence length, Δk the mismatch between the wavevectors of the qth harmonic k_q and the fundamental k_0

For phase matching it is desired that

$$\Delta k \longrightarrow 0$$

Harmonic and driver remain in phase – coherent build up of HHG
Signal grows quadratically over the length of the medium

Quasi Phase Matching HHG from Gases

$$\Delta K = mK - |\Delta k| \approx 0 \text{ where } K = \frac{2\pi}{L}$$

and $$L = 2mL_c$$

L_c the coherence length, is the distance over which HHG remains in phase and hence adds constructively

Harmonic generation is switched off periodically such that there is only emission from regions that are in phase.

(m (odd only) is the order of the process)

Quasi phasematching

$$\Delta k \approx \Delta kg_q + \Delta ke_q(t) - K$$

Waveguide dispersion

Free electron contribution to dispersion

QPM term for an m^{th} order process

As the intensity increases to achieve higher cut off energy in the harmonic spectrum $\Delta ke_q(t)$ increases

$\Rightarrow$ QPM period shortens accordingly

For very high orders L_c is on the order of a few microns

Quasi Phase Matching Schemes

Efficient generation of harmonics over an **interaction length >> L_c**

- **Peatross**: Counter propagating light

  => Selective zoning of harmonic generation by a standing field modulation

  S. Voronov *et al*., *Phys. Rev. Lett.* , **87**, 133902 (2001).

- **Murnane**: Modulated Capillaries

  => Switching on and off harmonic generation via intensity modulations in a capillary

  A. Paul *et al*., Nature, **421**, 51 (2003)

Propagation of Intense Ultrashort pulses in gas filled capillaries

Courtois et al Phys. Plas., 8, 3445 (2001)

Intensity modulations in a hollow capillary from **multimode beating**

For a Gaussian TEM_{00} free space mode

- Most energy coupled into the fundamental mode, EH_{11}, for

$$\frac{1/e^2 \text{ radius}}{\text{Capillary Bore radius}} = \frac{w_o}{a} = 0.64$$

- More energy coupled into higher order modes for $\frac{w_o}{a} < 0.64$

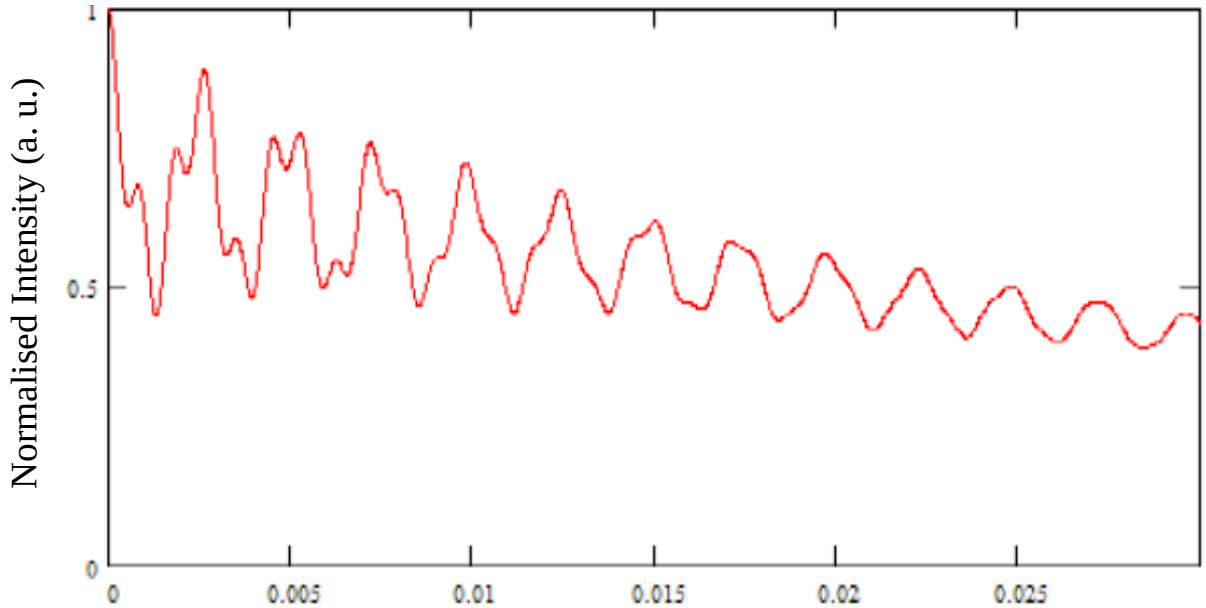
- More energy coupled into higher order modes for greater density of gas in capillary

Intensity profile for optimal coupling

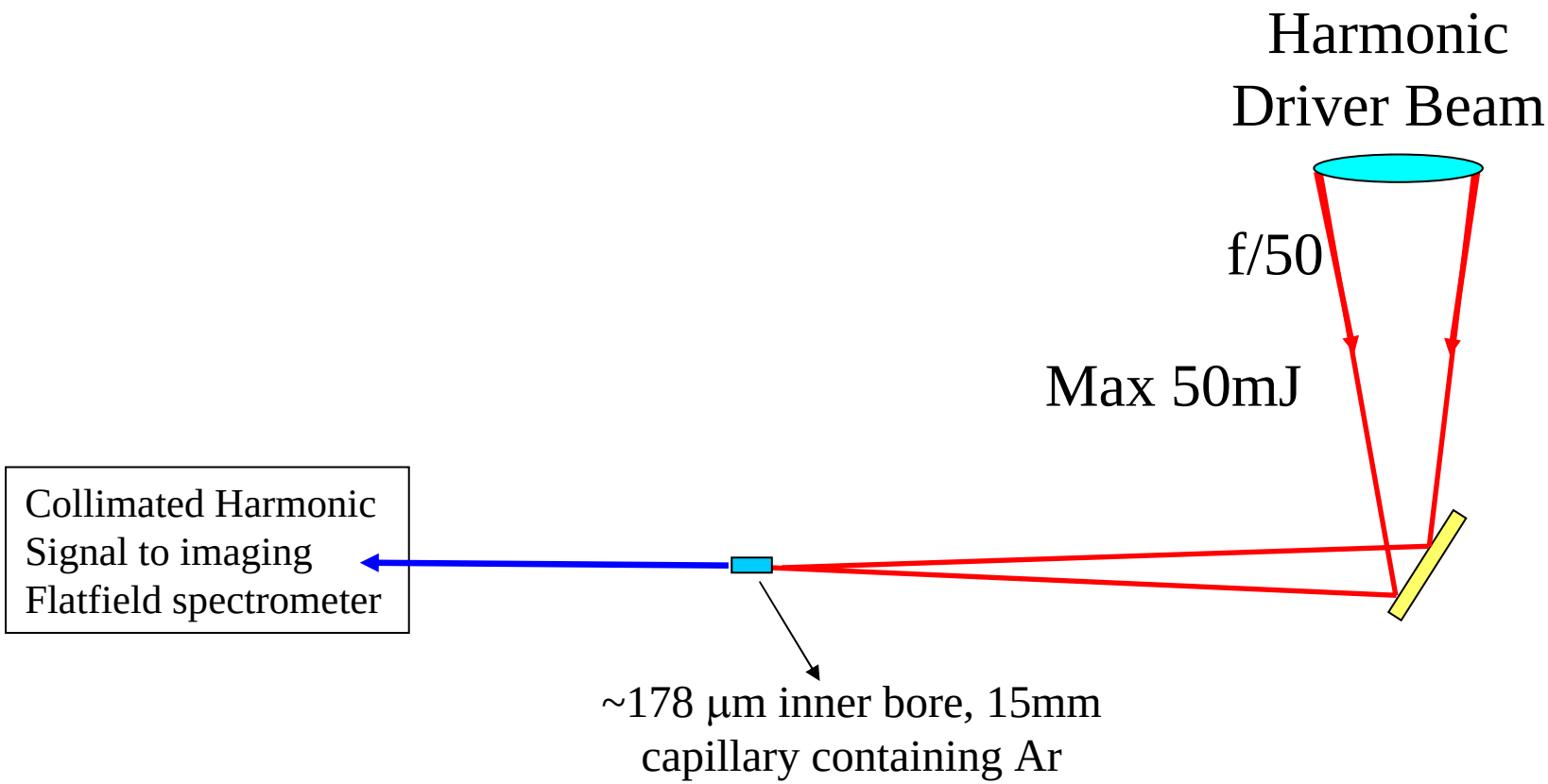
However even for a coupling coefficient of TEM_{00} $\frac{w_0}{a} = 0.64$

$\Rightarrow$ Significant intensity modulations over the attenuation lengths of the dominant modes

First 3 modes, weighted for optimal matching, $w_0/a = 0.64$



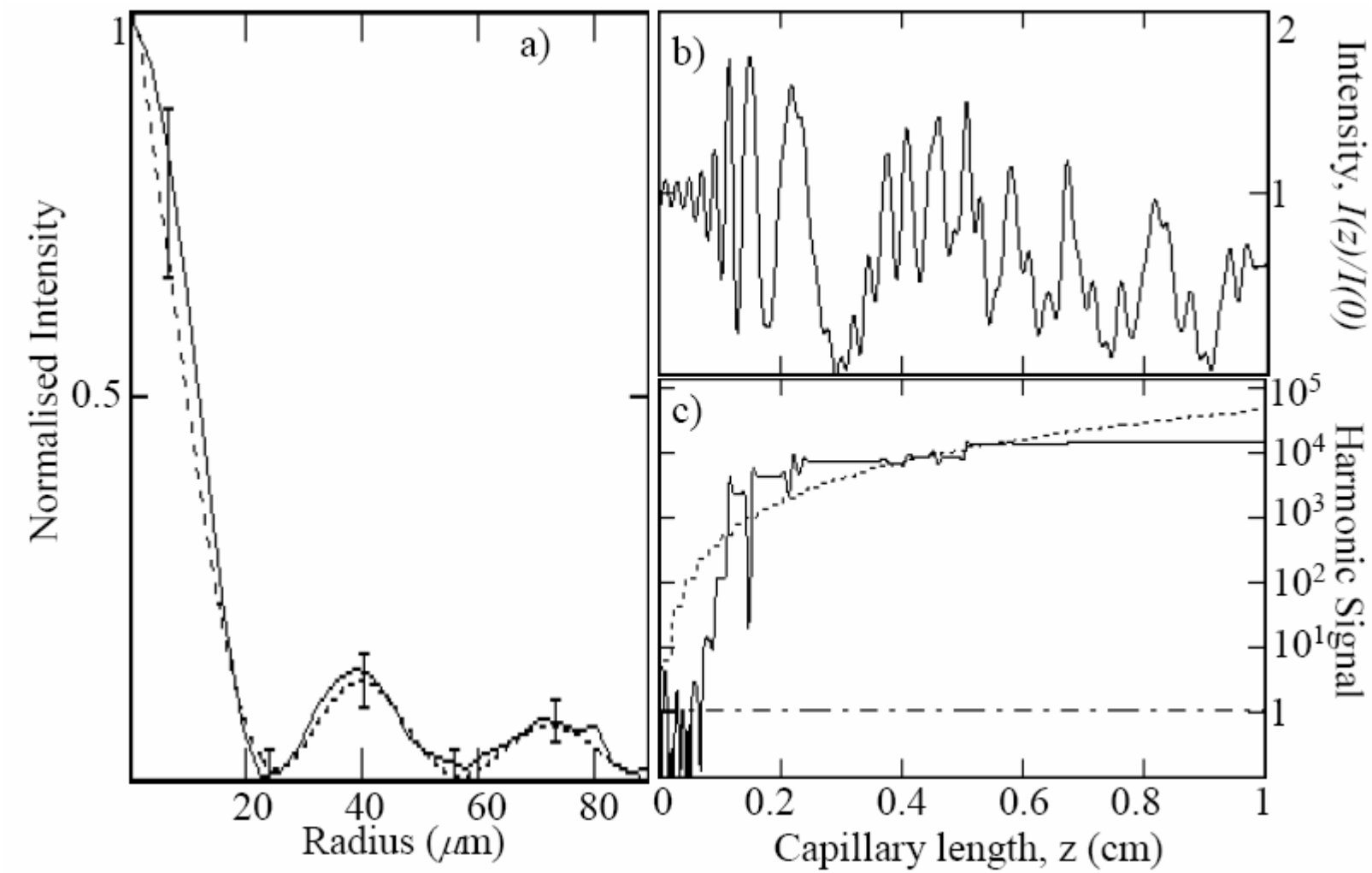
Experimental setup: Astra TiS Laser, ~ 40fs



Capillary Matching: $\frac{w_o}{a} \sim 0.2 - 0.3 << 0.64$

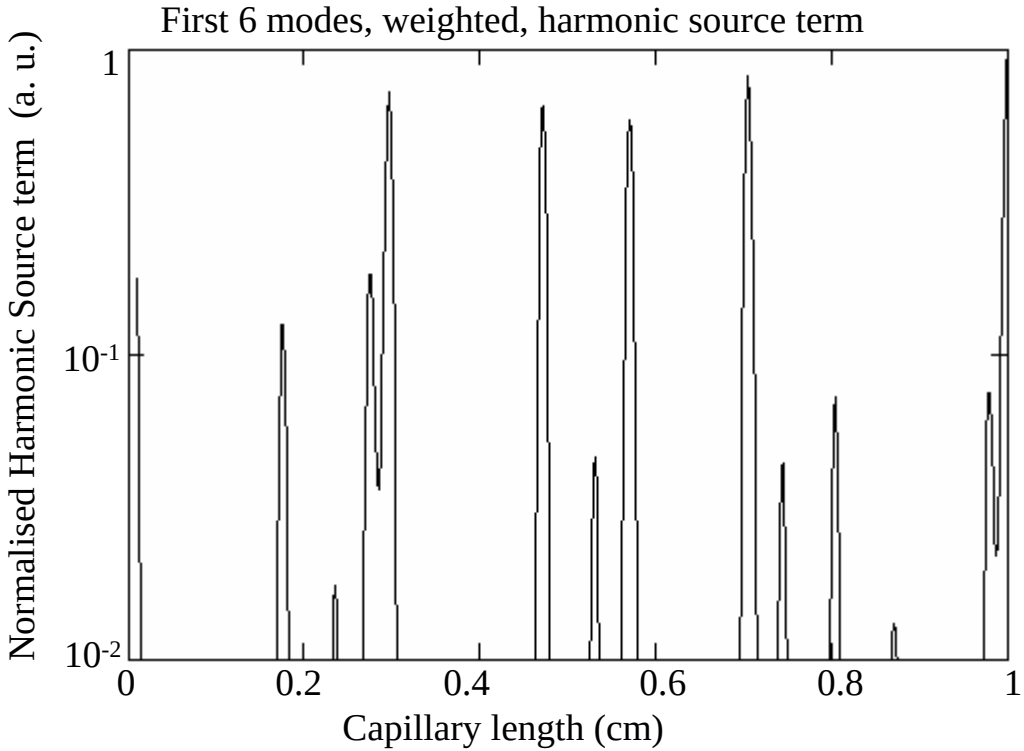
$\Rightarrow$ **Expect to excite several high-order capillary modes**

Intensity profile in capillary for $\frac{w_o}{a}$ = ~0.2



Harmonic source term in capillary

The resulting harmonic source term ~I^7

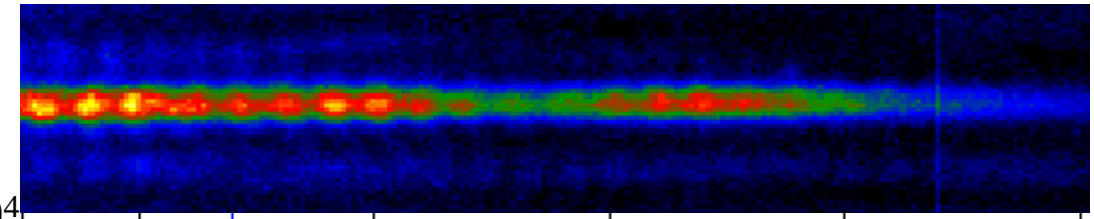


Significant modulation of Harmonic source term >10^2 on/off ratio

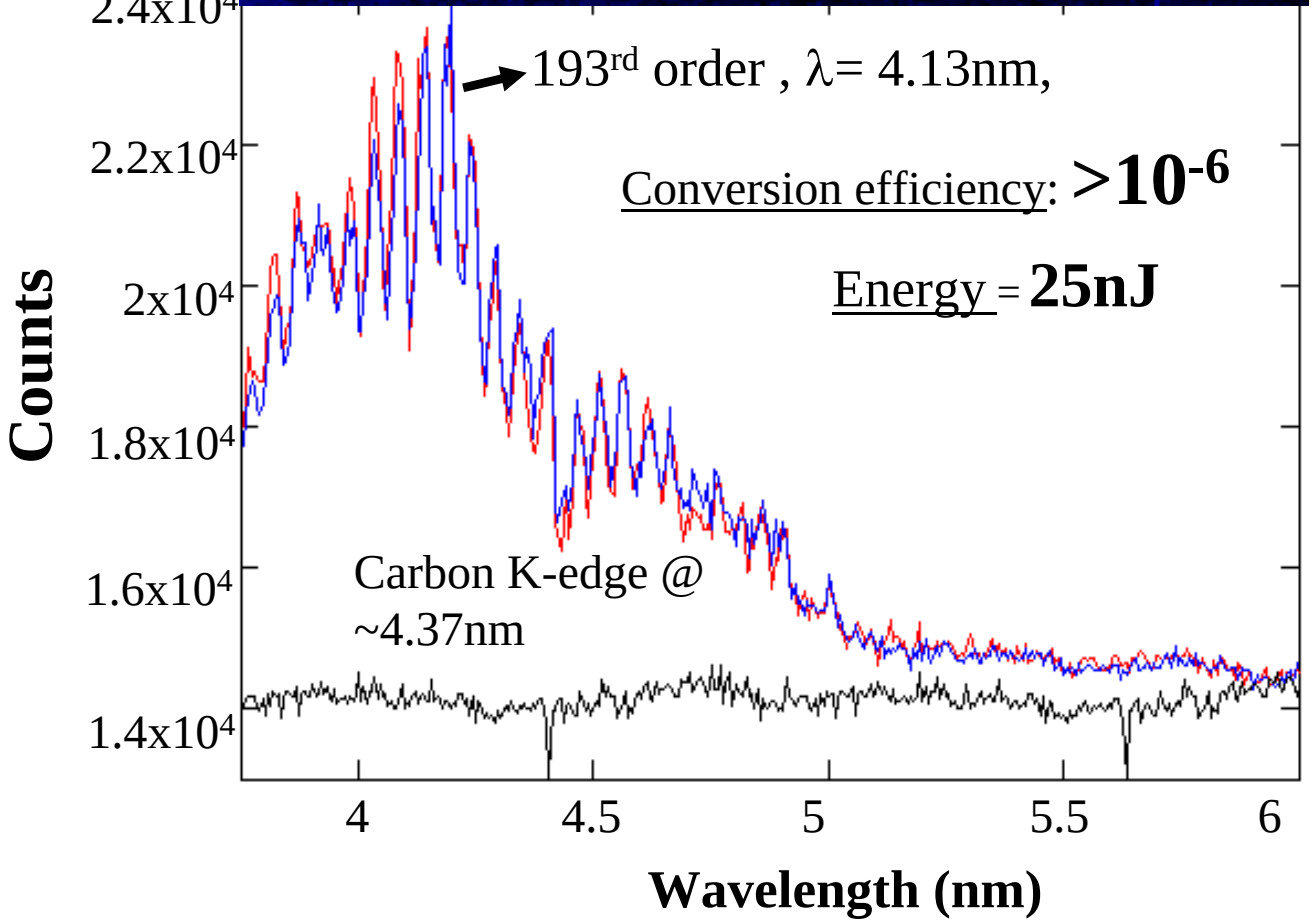
⇒ Dramatically reduced total ion fraction: <0.01

Imperfect m=1 QPM process possible

Experimental evidence for Bright QPM HHG from Ar ions



• **20mbar Ar**

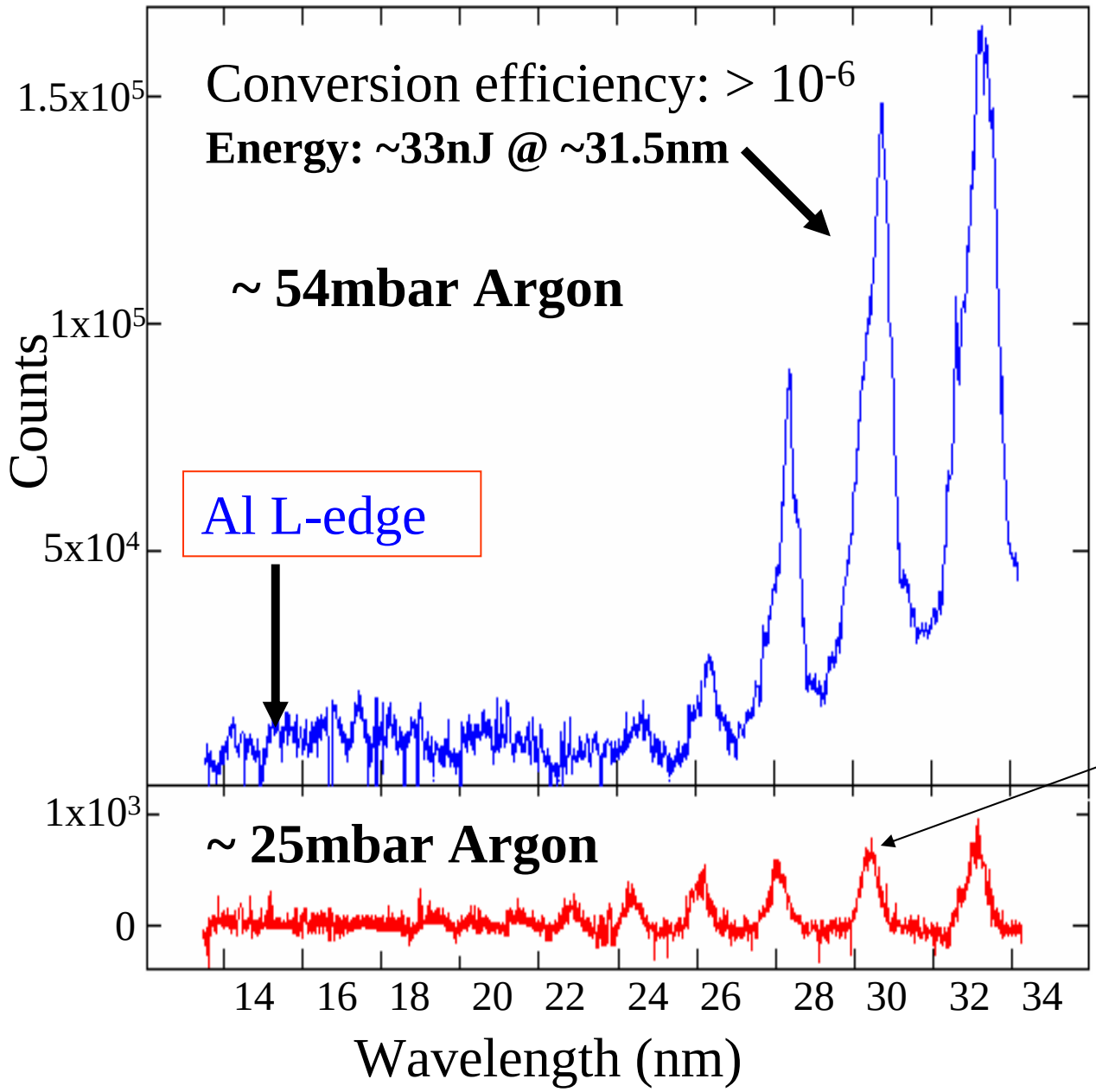


Flux ~ 10^{10} photons per harmonic peak per second

• **42mbar Ar**

Previous water window efficiency $\Rightarrow$ Conversion Efficiency **$<10^{-9}$**

QPM HHG from Argon:



$\frac{w_o}{a}$ = ~ 0.3

Density change x2 leads to <x200 signal

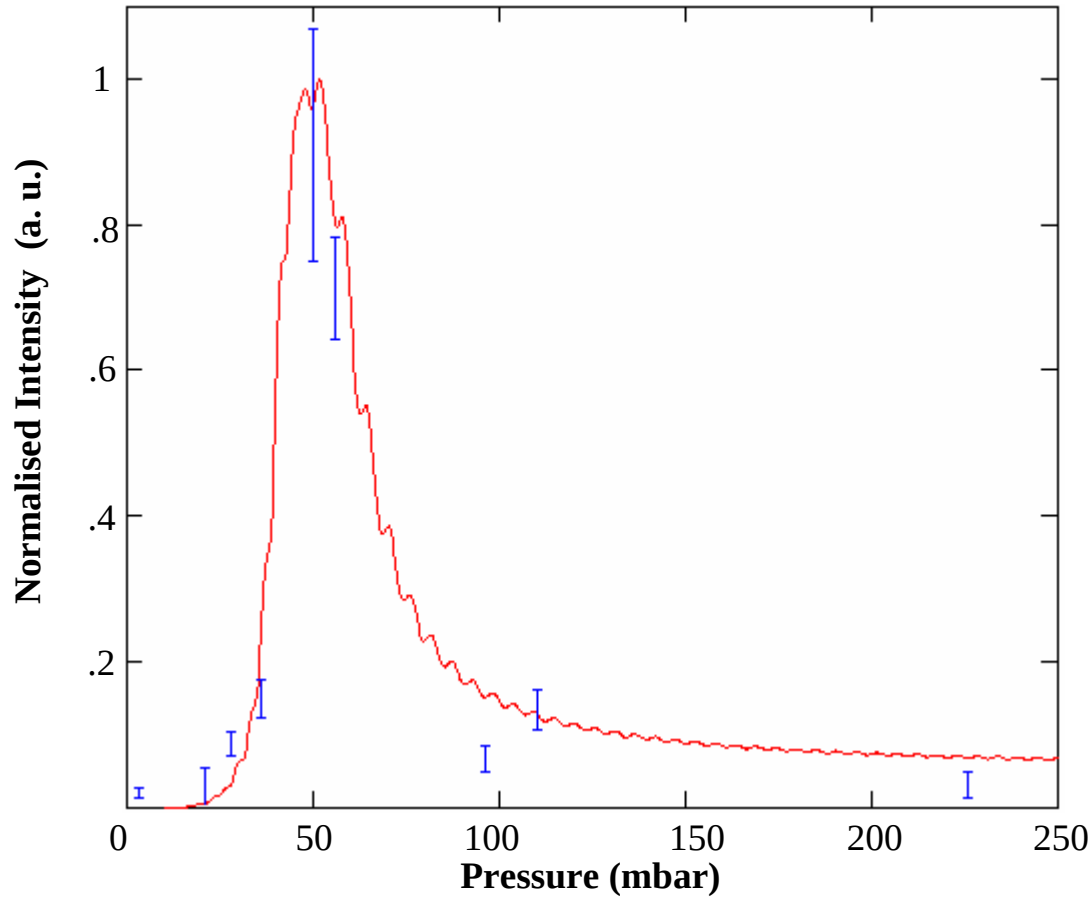
The harmonic signal drops rapidly

Conversion efficiency: ~5x10^{-9}

Energy: ~70pJ @ ~31nm

The harmonic signal slowly drops out to the l-edge

25th Harmonic in argon dependence with pressure



Summary

- QPM via intensity modulations due to fundamental and higher order mode beating in a hollow gas filled capillary
- Very bright water window harmonic emission from Argon ions conversion efficiency $>10^{-6}$
- Brightness $\sim 10^{21}$ photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)
- Flux $\sim 10^{10}$ photons per second (10Hz system)
- Typically tens of nJ per harmonic peak