Studies of High Order Harmonic Generation, Electron Acceleration and Intense X-ray Generation using Ti:Sapphire Laser Pulses

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Development, Science and Emerging Applications

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Raja Ramanna Centre for Advanced Technology

National R & D Centre for Lasers and Accelerators

- Total staff strength is ~1250 of which ~450 are scientists and engineers
- Laser Plasma Division : 25 scientists and engineers
- Ultrahigh intensity laser-plasma interaction

  (2006 onwards)

  - Coherent XUV-soft x-ray radiation (HHG / X-ray Lasing)
  - Laser driven electron acceleration
  - Intense X-ray generation and applications
  - Energetic ions/ protons/ neutrons/ γ rays

Outline

- High power laser systems
- Studies in ultrashort pulse, high intensity laser plasma interaction
  - High order harmonic generation from pre-formed plasma plumes
  - Resonant intensity enhancement of single harmonics
  - Laser driven electron acceleration
  - Intense X-ray emission from carbon nano-fibres
  - Ultrashort pulse K-α X-ray line emission
  - Fast electron generation / MeV X-ray Bremsstrahlung
- Conclusion

High Power Laser Systems

1 TW, 1 ps Nd: Glass Laser

1 J , 1 ps laser pulses

Highly stable regenerative amplifier

Opt. Commun. 25, 369 (2005)

10 TW, 45 fs Ti: Sapphire Laser

Peak intensity ~ 2 x 10^{18} W/cm^2

Studies of ultrashort pulse, high intensity laser-plasma interaction

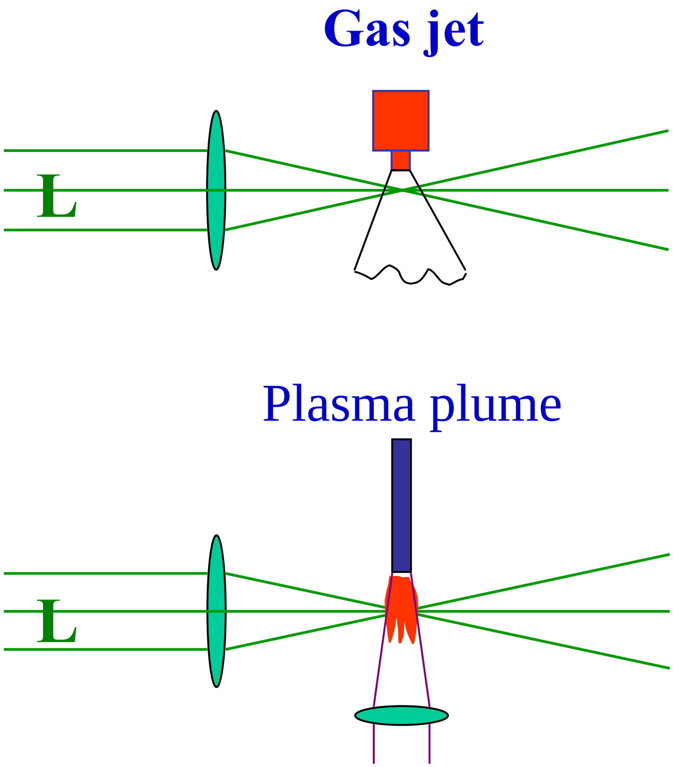
150 TW, 25 fs Ti: Sapphire Laser

Under procurement

(For studies at higher intensities in the relativistic regime)

High Order Harmonic Generation

Harmonic Generation from Preformed Plasma Plumes



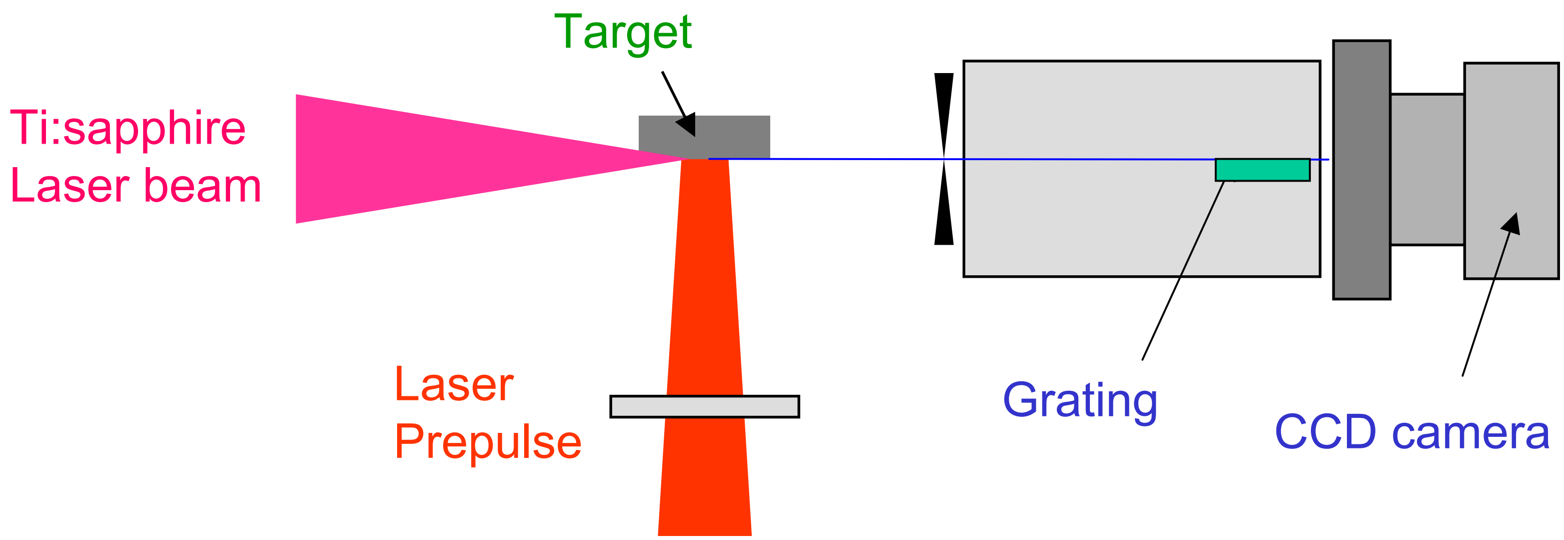
- Low intensity harmonics
- Intensity increase by ≥ 1000X desired
- Resonance enhancement of single harmonic by coinciding it with some atomic resonances

Plasma can be produced from most elements (or their compounds)

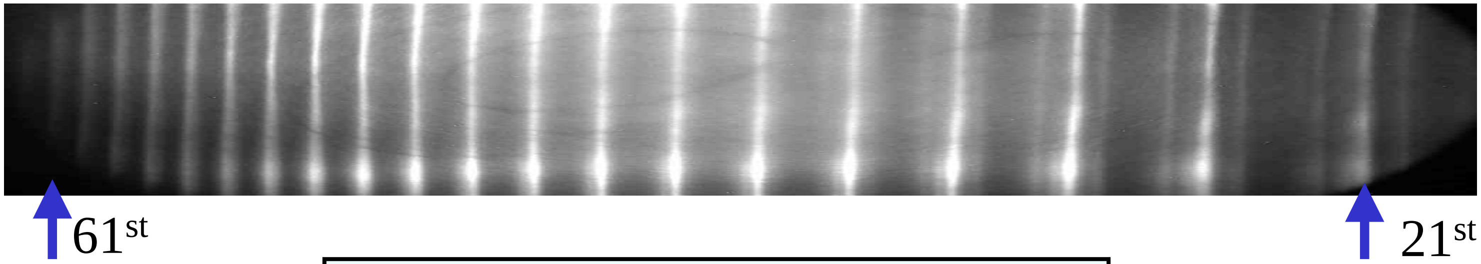
→ Greater possibility of atomic / ionic resonances

Also higher rep rate operation possible

Generation of Intense Coherent X-ray Radiation



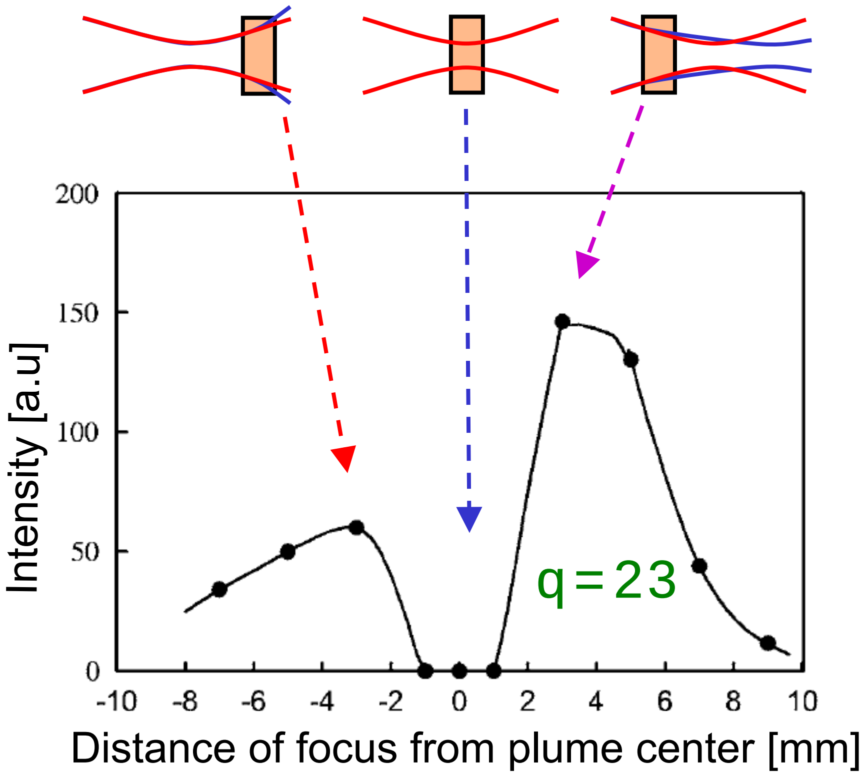
Spectrum of high order harmonics from silver plasma



Appl. Phys B 87, 243 (2007)

Coherent x-ray radiation at several discrete wavelengths down to 12.9 nm is produced

Optimization of Laser Focus Position



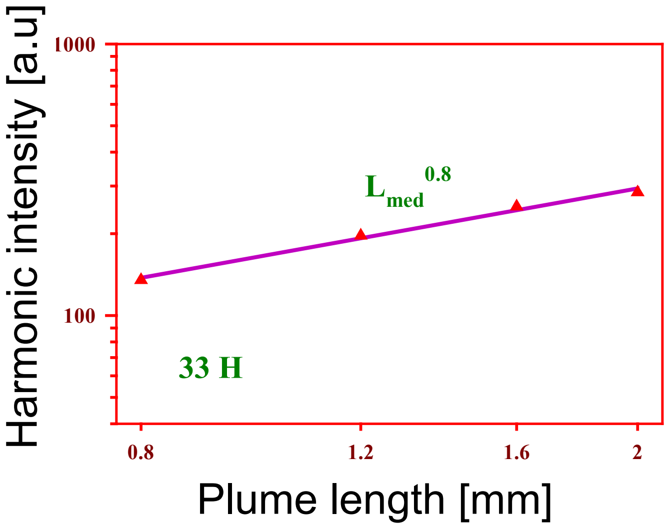
Silver plasma plume

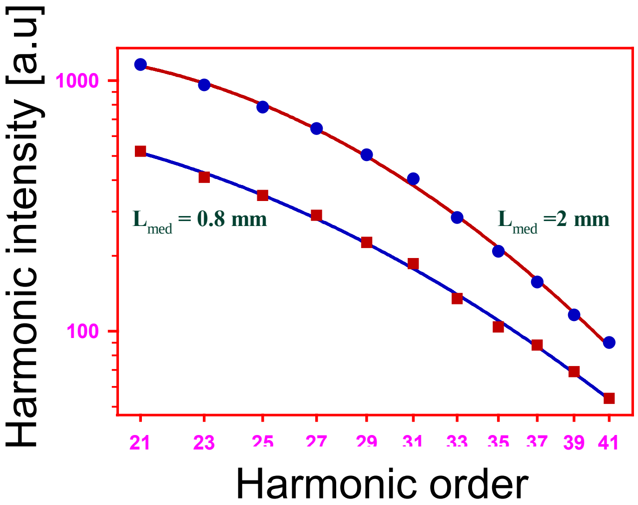
- Focus at plume center : high n_e
  - Large phase mismatch
  - Harmonic intensity vanishes
- Radial ionization gradient
  - Self-defocussing
- Laser focus before plume centre : more divergence → smaller intensity
- Laser focus after plume centre : reduced divergence → higher harmonic intensity

J. Opt. Soc Am. B 23, 2535 (2006)

J. Appl. Phys. 103, 013107 (2008)

Dependence of Harmonic Intensity on Length of Plasma Medium





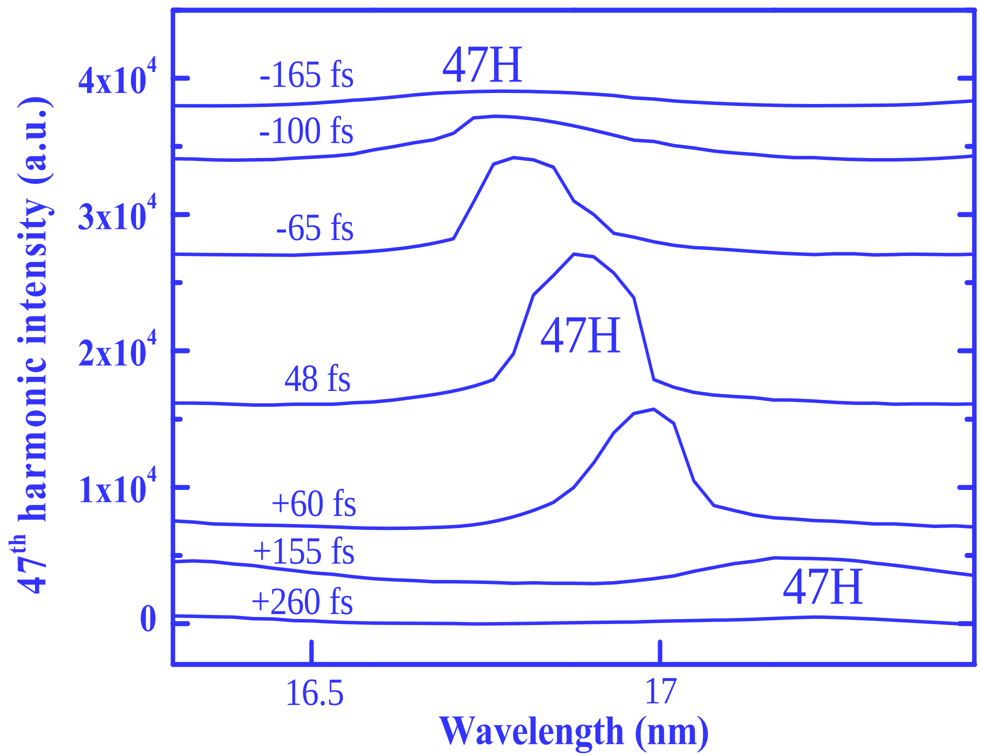
$$E_q = \int_0^{Lmed} N_0 d(q\omega_L) \exp\left(\frac{i\pi z}{L_{coh}}\right) \exp\left[-\frac{(L_{med} - z)}{2L_{abs}}\right] dz$$

- Coherent radiation : $I_q \propto L^2_{med}$
- Slower scaling ($I_q \propto L^{0.8}_{med}$) occurs due to increasing phase mismatch and harmonic absorption with increasing length of plasma plume

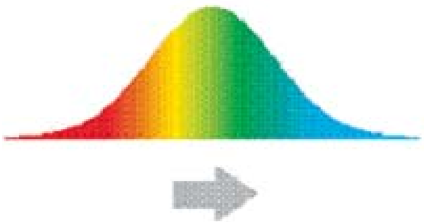
Tuning of Harmonic Frequencies

Harmonics are produced in the initial part of the laser pulse as the phase matching condition is spoilt by overionization at higher intensities

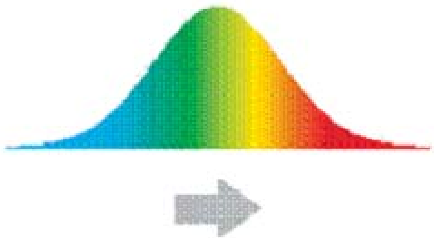
Effect of Chirp Variation



Negatively Chirped Pulse



Positively Chirped Pulse



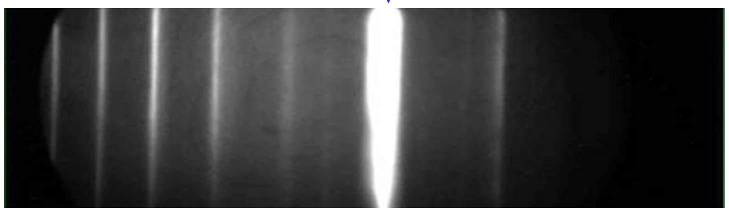
Harmonic tuning range ~ 0.8 nm

J. Opt. Soc. Am. B 24, 1138 (2007)

Intensity Enhancement through Harmonic Tuning

Indium Plasma Harmonics

13 H

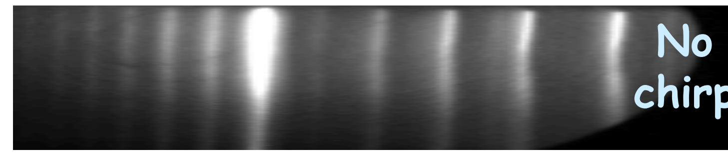


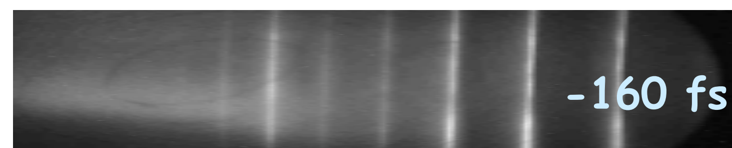
13th harmonic: 200 X

Phys. Rev. A 74, 63824, (2006)

Chromium Plasma Harmonics

29th H





27th H

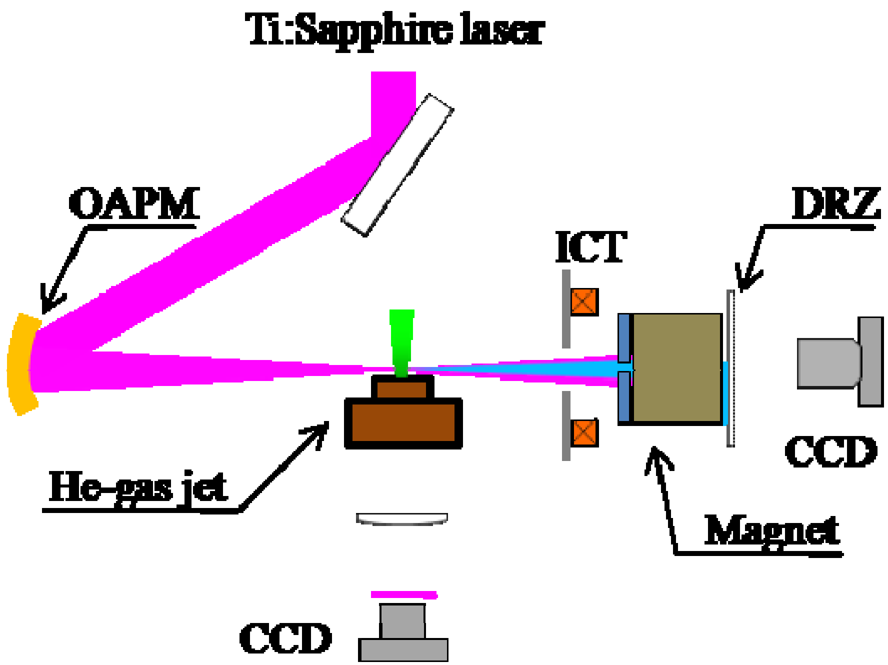
Harmonic frequency tuning

Enhancement / extinction

Optics Letters 32, 65 (2007)

Laser Driven Electron Acceleration

Electron Acceleration Experiments



- ❑ Laser : 10 TW, 45 fs
- ❑ Slit-type supersonic nozzle
- ❑ $I_L \approx 1.8 \times 10^{18}$ W/cm^2
- ❑ N_e : 5 – 9 x 10^{19} cm^{-3}

IEEE Trans. Plasma Sci. 36, 1694 (2008)

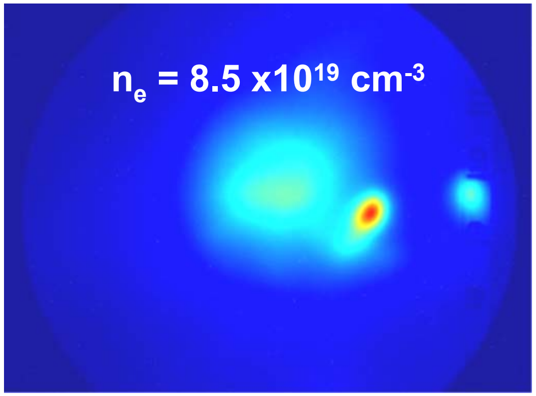
❖ Self-Modulated Laser Wakefield Regime

- Electron beam profile, beam energy, total beam charge
- Forward Raman Scattering (density measurement)
- Effect of laser chirp on electron beam charge

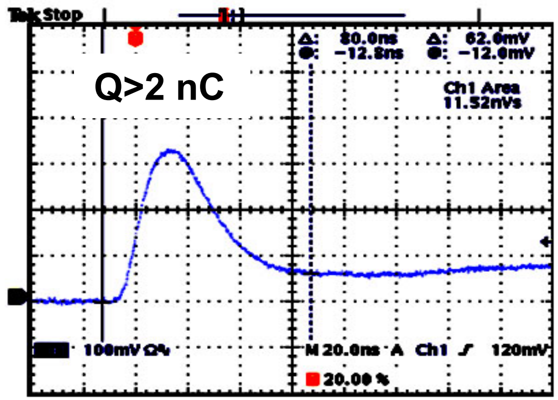
❖ Well collimated, monoenergetic electron beam with minimum divergence of ~ 4 mrad in energy range of 10 – 20 MeV

Electron Acceleration : Experimental Results

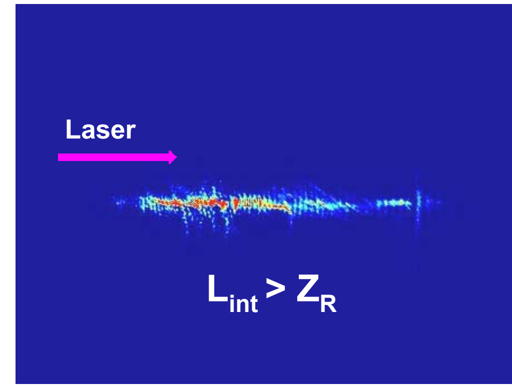
Electron beam profile



Electron beam charge



Relativistic self-focusing

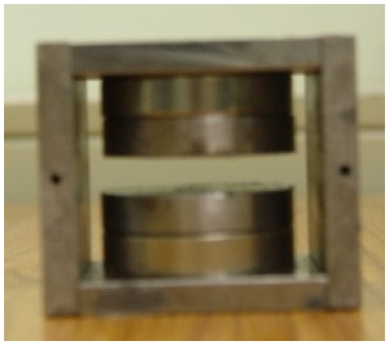


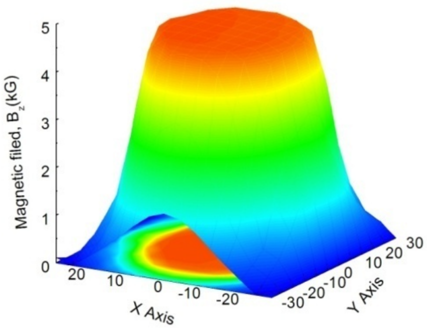
- For $n_e > 5 \times 10^{19}$ cm^{-3}, electron beam was produced in each laser shot with total charge > 2 nC
- Most measurements done at $n_e \sim 8.5 \times 10^{19}$ cm^{-3}. Beam divergence < 10 mrad is observed, minimum divergence ~ 4 mrad
- Side-imaging of incoherent Thomson scattered laser light shows occurrence of relativistic self-focusing

Energy Spectrum of Electron Beam

Electron energy spectrograph

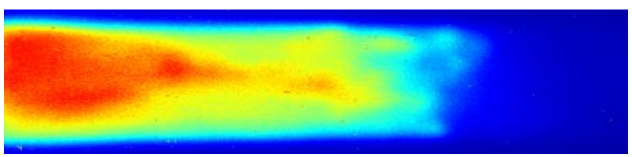
(Energy range : 6 – 50 MeV)

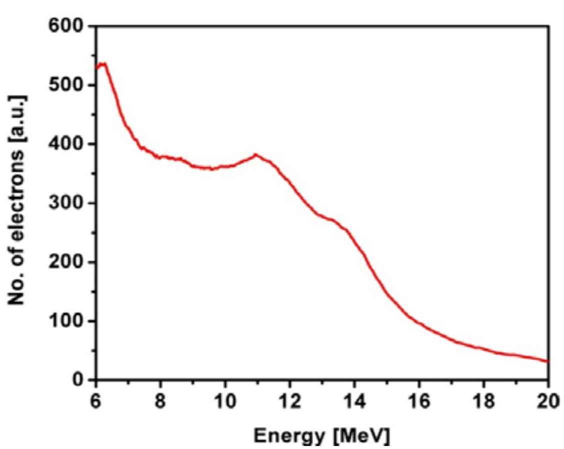




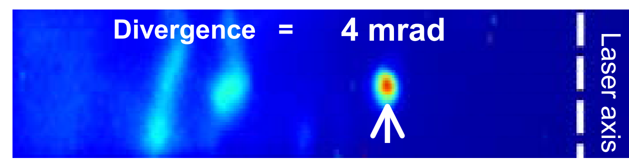
- Monoenergetic beam at n_e ~8.5 x 10^{19} cm^{-3} (~ 20 % of shots)
- Peak energy : 10 – 20 MeV with energy spread of ΔE/E < 4 % (limited by spectrograph resolution)

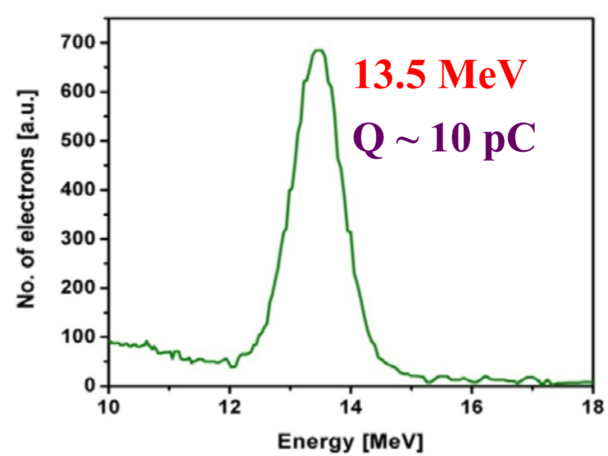
Continuous energy spectrum





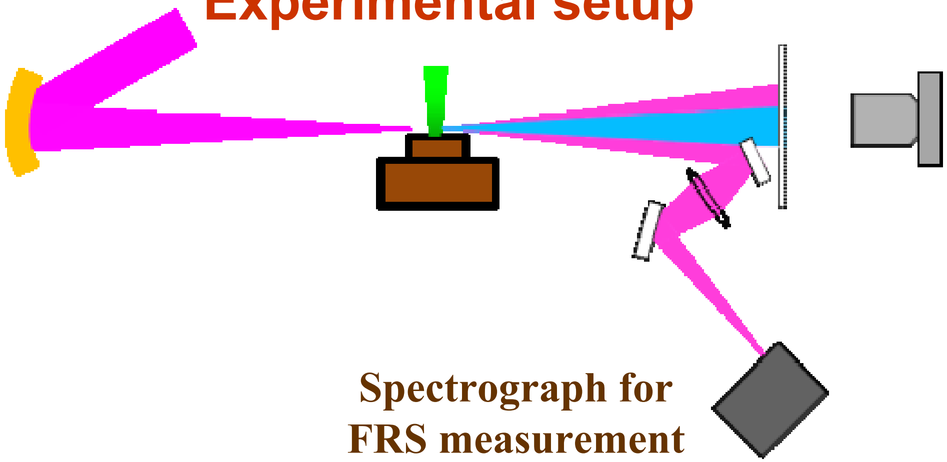
Monoenergetic spectrum



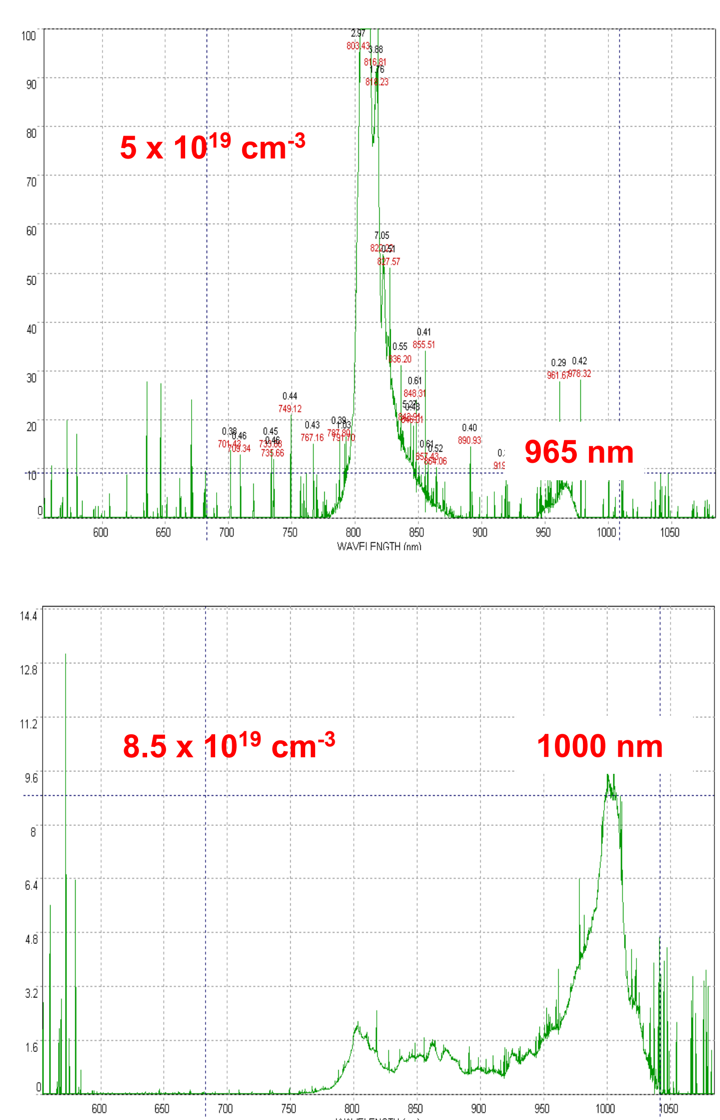


Forward Raman Scattering (FRS)

Experimental setup

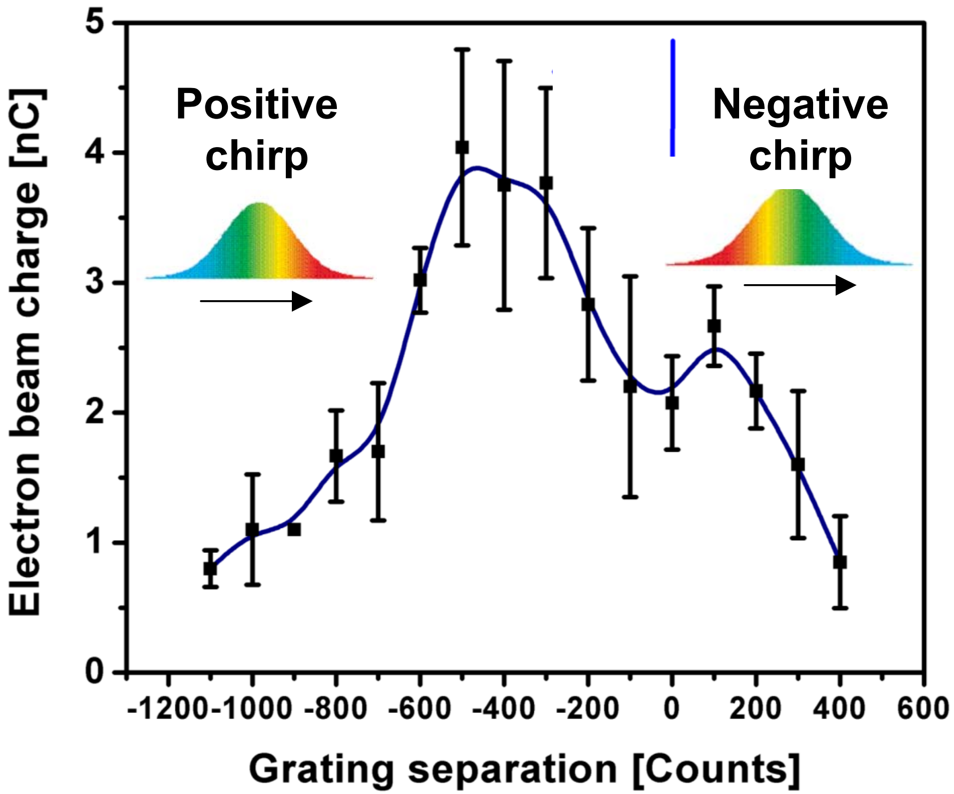


FRS Spectrum



- FRS : Occurrence of self-modulation
- Electron density from wavelength shift of Raman satellite in good agreement with interferometry measurements
- At high electron density, Raman satellite broadens

Effect of Laser Chirp on Beam Charge



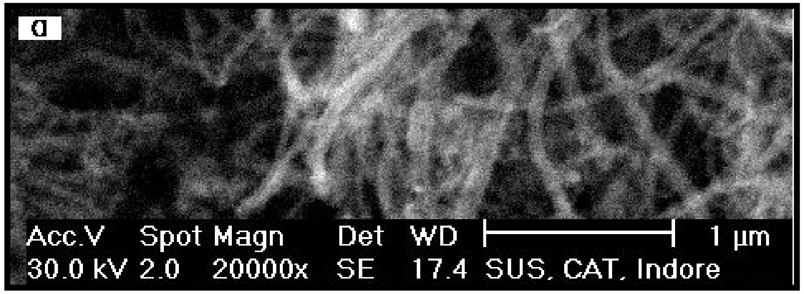
- Positive chirp up to a certain value increases electron beam charge
- Negative chirp decreases the electron beam charge
- Variation in beam charge with laser chirp may arise due to wavelength dependent group velocity which affects self-modulation of the laser pulse

Intense X-ray Generation

(Sub - keV, Multi - keV, MeV)

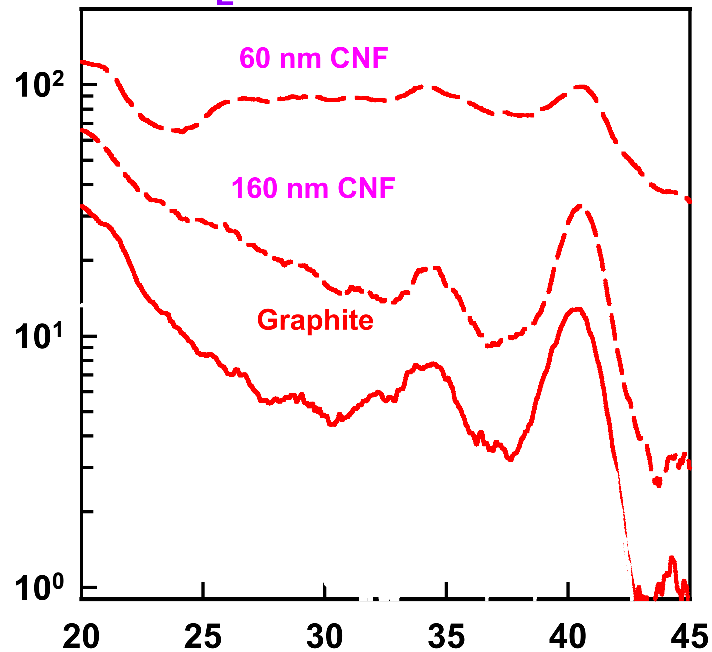
Enhanced X-ray Emission in the Water-Window Region

Target : Carbon Nano-fibres (CNF) and Graphite



SEM picture of CNF target

I_L = 4 x 10^{17} W/cm^2



Resonant field enhancement

$$E_{in} = \frac{2E_0}{\varepsilon + 1}, \qquad \varepsilon = 1 - \frac{n_e}{n_c}$$

Resonance at $n_e = 2n_c$

$$\tau_R = \frac{r_0}{c_s}\left(\sqrt{\frac{n_0}{2n_c}} - 1\right)$$

60 nm CNF vs Graphite

- **Enhancement ≈ 18 X for $\tau_L \approx$ 45 fs**
- **Enhancement ≈ 28 X for $\tau_L \approx$ 300 fs**

High Brightness Monochromatic K-α X-ray Line Emission

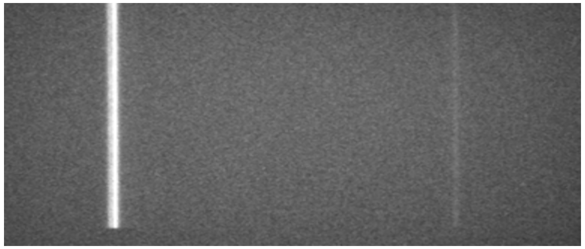
(For High Resolution Ultrafast X-ray Diffraction etc.)

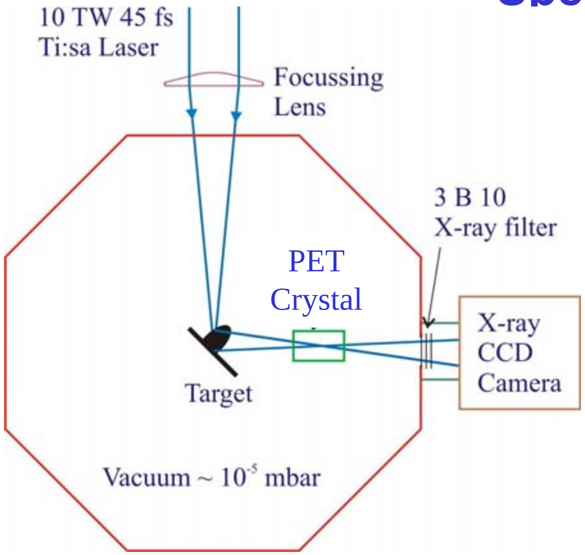
Target : Titanium foil

Laser : 10 TW, 45 fs

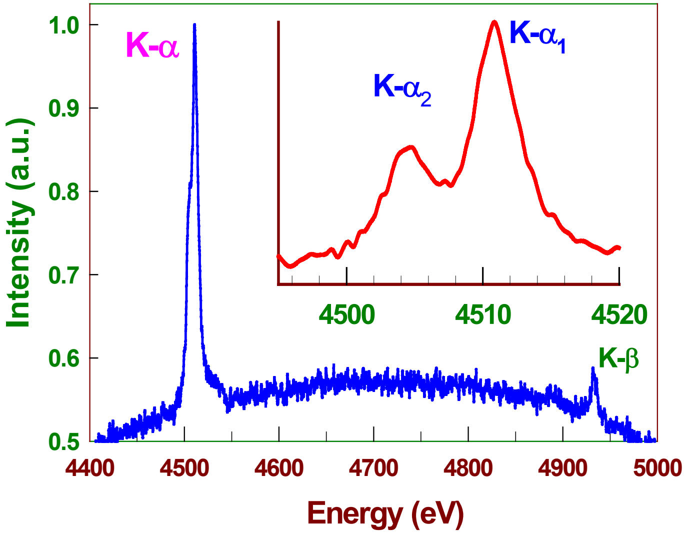
X-ray Crystal Spectrograph

Spectral resolution : 3.9 eV





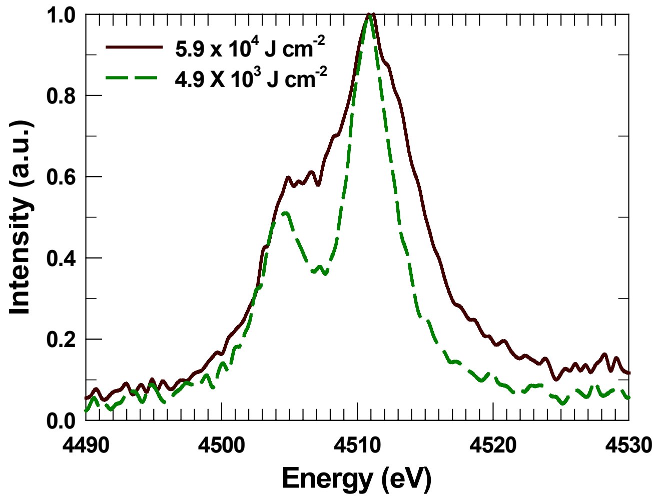
K-α_1 : 4510.8 eV
K-α_2 : 4504.9 eV
K-β : 4931.8 eV



❖ Look for laser / target irradiation parameters to produce small spectral width of K-α line

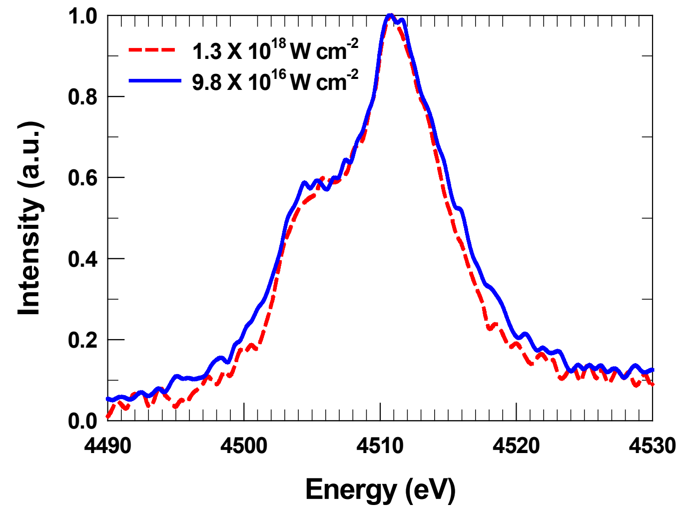
Spectral Broadening of K-α X-ray Line

Different laser fluences
Constant Intensity ≈ 10^{17} W cm^{-2}



Spectral width increases from 4.2 eV to 8.8 eV for higher laser fluence

Different laser intensity & pulse duration
Constant Fluence ≈ 5.9 x 10^4 J cm^{-2}



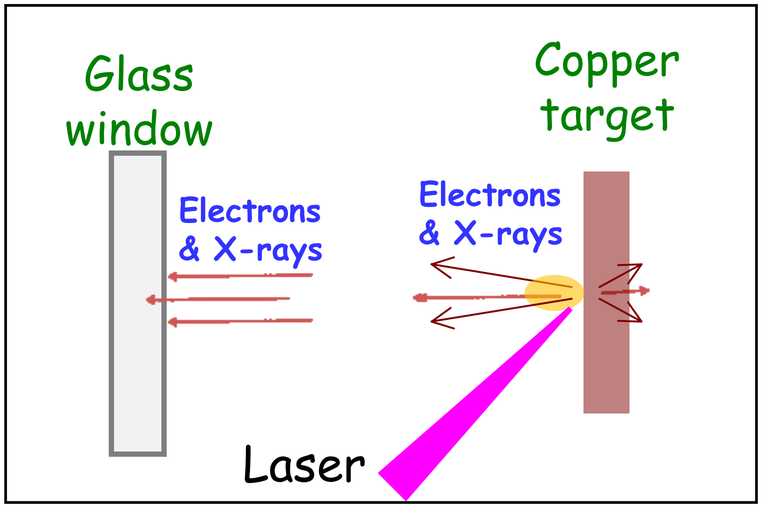
At constant fluence, no change in spectral width for two widely different laser intensities

⇒ **Spectral width of K-α radiation is closely linked to the laser fluence**

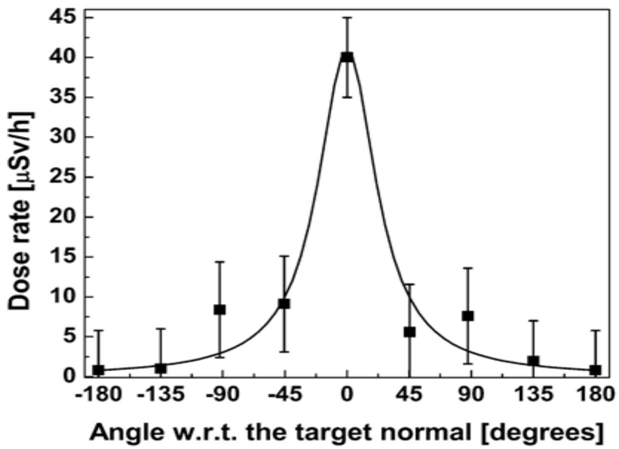
- **Increase in laser fluence is accompanied by increase in pre-pulse intensity**
- **Prepulse produces low temperature plasma in front of the target**
- **Observed spectral broadening occurs due to blending of blue-shifted K- α line from Ti^{1+} to Ti^{7+} ions present in plasma with neutral Ti K- α line**

MeV Bremsstrahlung X-ray Emission

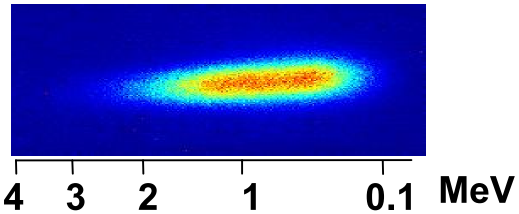
- $I_L \approx 1.3 \times 10^{18}$ W/cm^2, $\tau \approx 45$ fs



Angular distribution ($h\nu$ > 40 keV)



Energy spectrum of electrons



- **Electrons with energy up to ~2 MeV**
- **Two sources of hard X-ray radiation :**
  - **One at target (electrons going into the target)**
  - **The other in glass window of plasma chamber**
- **The second source gives rise to observed anisotropic distribution**

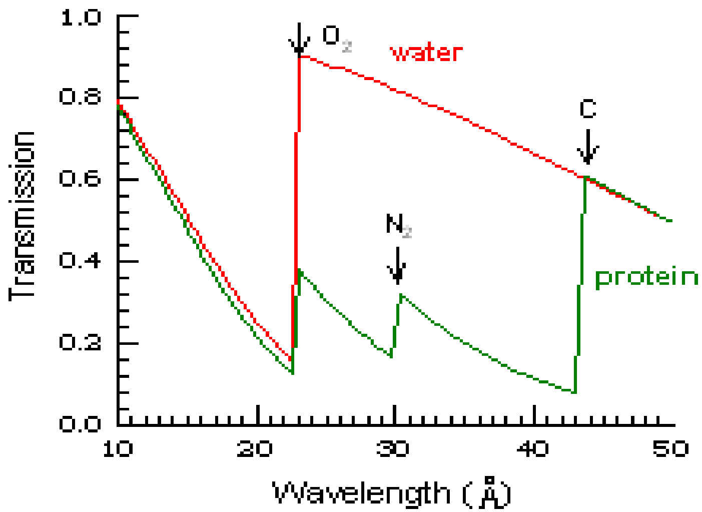
J. Appl. Phys. 102, 063307 (2007)

Narrow-Band Water Window X-ray Emission

(For Live X-ray Microscopic Imaging)

Water-window

23 Å - 44 Å

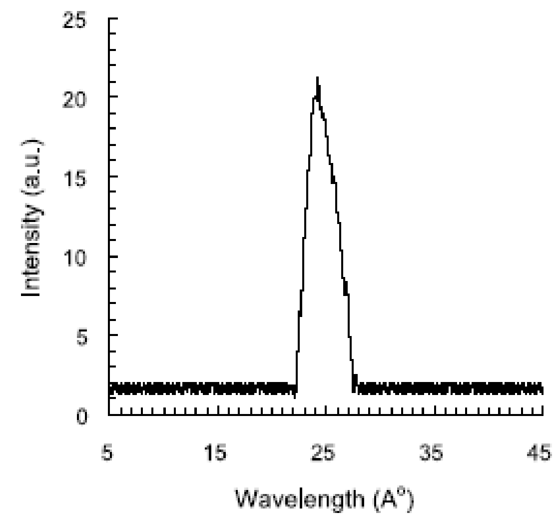


Gold-copper mix-z plasma

Appl. Phys. Lett. 83, 27 (2003)

Free-standing Al / V filter

Transmitted x-ray spectrum



Appl. Phys. B 86, 519 (2007)

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Thank you