Compact Ultrafast X-Ray Point Source

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**Concept:**
Trigger a sharp field emission tip in a fs laser, and accelerate/focus electrons onto x-ray target

- nm source size
- high brightness
- fs time resolution
- coherent electrons
- tabletop system

**Setup:**
Cold-cathode field emission tip
- Radius \( r_p \), 20 to 150 nm
- Electrochemically etched
- Columbic work function 4.5 eV
- Hafnium Carbide (3.5 eV)

X-ray Target:
- 500 nm Cu for \( K_a \)
- deposited on Be foil
- Biased to +20 kV

Microchannel Plate Detector MCP
- Tip imaged with magnification \( \sim 10^3 \)
- Single-atom resolution possible by field ion microscopy method
- Single-electron detection, Gain \( \sim 10^3 \)
- Sensitive x-ray detection

**Laser-triggered electron emission:**
- DC emission
  - Apply large field (GV/m) to surface using sharp tip as a lightning rod
  - Electrons tunnel through barrier
  - Emission current is extremely nonlinear in the DC bias voltage
- Photo-field emission
  - Electrons in the metal are excited by the laser (absorption of one or more photons)
  - Effectively, work function \( \gamma \) is reduced
  - Dominant at low laser power
  - Emission is function of pulse ENVELOPE
- Optical field emission
  - The laser’s electric field directly modulates the barrier for correct polarization
  - Dominant at high laser power
  - Emission current is a function of laser FIELD

**Ultrafast electrons:**
1. Photo-field emission observed
   - Fowler-Nordheim plot reveals effective work function decreased by 1.5 eV with low-intensity in Tungsten

2. Over-the-barrier emission in HFC
   - Auger decay
   - L-shell hole
   - M-shell hole \( \rightarrow \) \( Z+ \) (ion) \( Z++ \) (doubly ionized)
   - Rapid Coster-Kronig decay
   - Lasing

3. Optical field emission inferred

4. Pulsed electrons in the time domain
   - Time-of-flight measurement
   - Numerical integration of wavefunction reveals sub-fs emission
   - X-ray gain

5. Harmonics of electron rep rate
   - X-ray laser energy level diagram
   - "Cylindrical" electron laser shown; small concentric cylinder geometry helps with space-charge difficulties

**Initial Ultrafast X-Ray Results:**

**Precision timing**
This x-ray signal was measured with only 20 x-rays per second detected.

1. DC emission
   - "Sharpness" of shadows used to determine x-ray spot size
   - X-ray shadow of a thin wire in the chamber
   - X-ray shadow of the x-ray target’s edge

2. Photo-field emission
   - "Imaging" with ultrafast x-rays
   - (grainy pattern from lower SNR due to low flux of fs x-rays)

3. Optical field emission
   - knife edge
   - Laser x-ray current

4. Pulsed electrons in the time domain
   - Time-of-flight measurement
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5. Harmonics of electron rep rate
   - X-ray laser energy level diagram
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**Extension: Line Source, X-Ray Laser:**

X-ray laser concept: traveling wave optical field emitter

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- Would hugely improve brightness, directionality
- Ultrafast, coherent x-rays
- High peak brightness
- Tabletop source
- Optical field emission is the enabling technology
- Requires \( 10^{11} \) A/cm\(^2\) current density at gain medium for laser
- Material damage is of concern
- Pump pulse should be same duration as K-hole lifetime

**Space-Based X-Ray Communications Concept:**

**Ultrafast xray point-source**
- Orders of magnitude advance in timing resolution over state-of-the-art
- Extremely high peak brightness
- Tiny footprint \( (<0.5 \text{ m}^2) \)
- \( 10^{11} \) A/cm\(^2\) current densities have been demonstrated with field emission tips
- For 10-fs pulses, this peak current density yields \( \sim 100 \) to \( 1000 \) electrons
- At 1-GHz rep-rate, this yields \( 10^8 \) precision-timed x-rays per second

- \( a \)-frequency X-rays for very low diffraction during propagation

- Power inefficient, compact design
- 30 mW, 36 fs compact fiber laser

- Precision timing: only 20 x-ray photons per second needed for 10-Hz BW communications
- Demonstrated in field-of-principle experiment already
- Lasing occurs on inner-shell transitions
- Core holes have \( \sim \) several fs lifetimes due to Auger decay
- Pumping must be fast!

**Ultrafast electrons**
- 200 fs laser pulses
- Photo-current from x-ray laser
- Photodiode w/ 20-dB amp

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