Compact Ultrafast X-Ray Point Source

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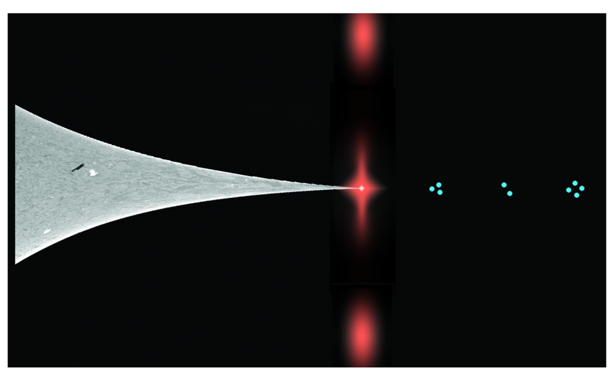
Concept:

Trigger a sharp field emission tip with a fs laser, and accelerate/focus electrons onto x-ray target

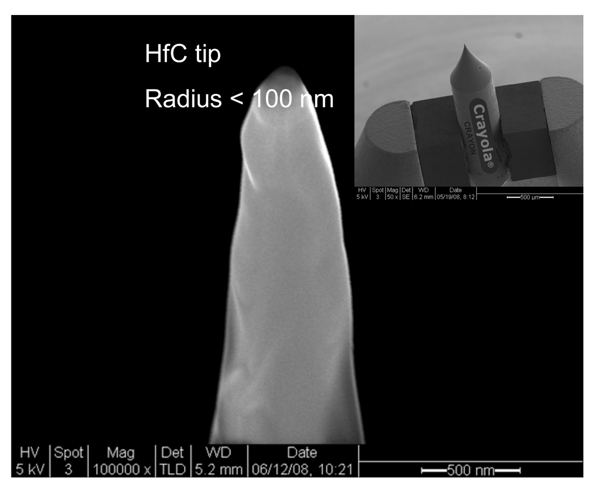
- nm source size
- high brightness
- fs time resolution
- coherent electrons
- tabletop system

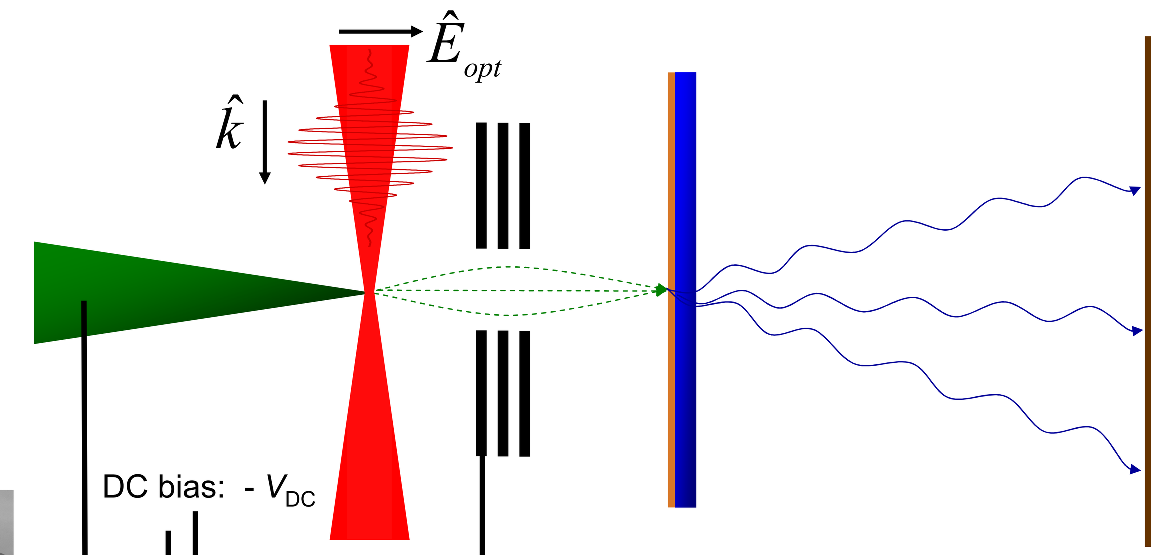


Setup:

Cold-cathode field emission tip

- Radius r_{tip} 20 to 150 nm
- Electrochemically etched
- Tungsten (work function 4.5 eV)
- Hafnium Carbide (3.5 eV)





X-ray Target:

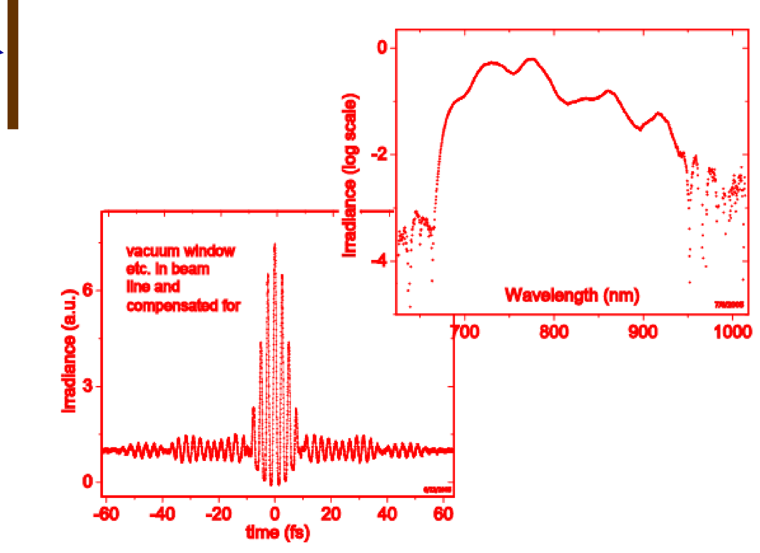
- 500 nm Cu for Cu K_α 8-keV
- deposited on Be foil
- Biased to +20 kV

Ultrafast laser

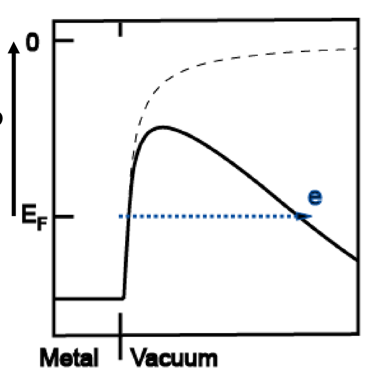
- Titanium sapphire
- Pulse duration < 10 fs
- Rep rate 150 MHz
- Avg. power ~ 100 mW at tip

Microchannel Plate Detector MCP

- Tip imaged with magnification ~ 10^5
- Single-atom resolution possible by field ion microscopy method
- Single-electron detection, Gain ~ 10^6
- 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

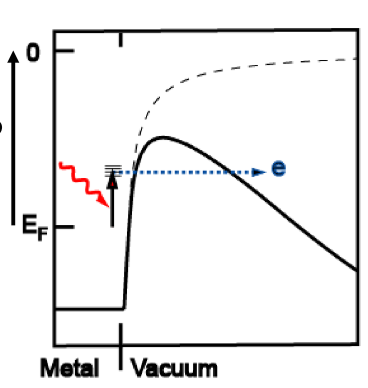
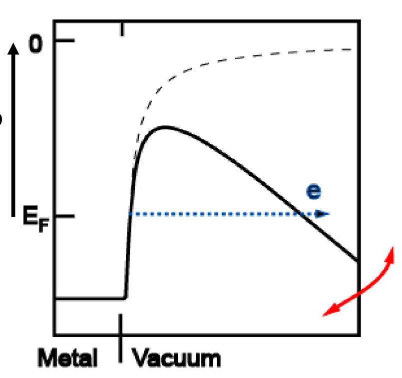


Photo-field emission

- Electrons in the metal are excited by the laser (absorption of one or more photons)
- Effectively, work function φ is reduced
- Dominant at low laser power
- Emission is function of pulse ENVELOPE



Optical field emission

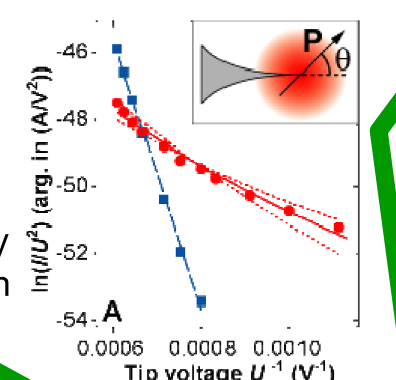
- The laser's electric field directly modulates the barrier for correct polarization
- Dominant at high laser power
- Emission current is a function of laser FIELD

Ultrafast electrons:

1. Photo-field emission observed

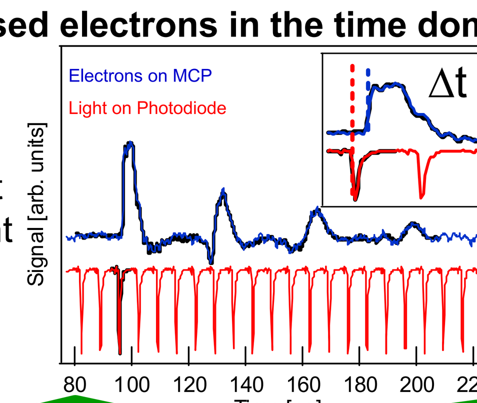
Fowler-Nordheim plot reveals effective work function decreased by 1.5 eV with low-intensity in Tungsten

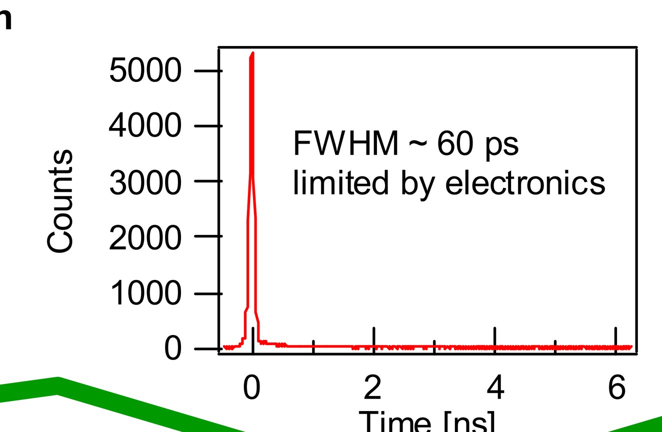
Hommelhoff et. al., PRL **96** (2006)



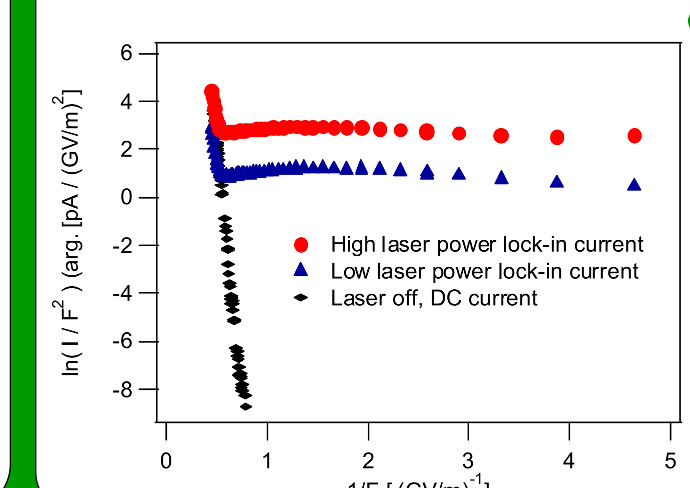
4. Pulsed electrons in the time domain

Time-of-flight measurement



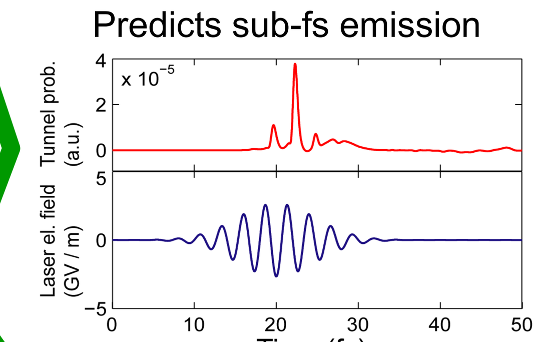


2. Over-the-barrier emission in HfC

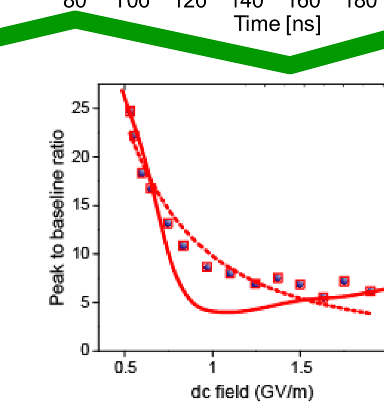


3. Optical field emission inferred

Predicts sub-fs emission

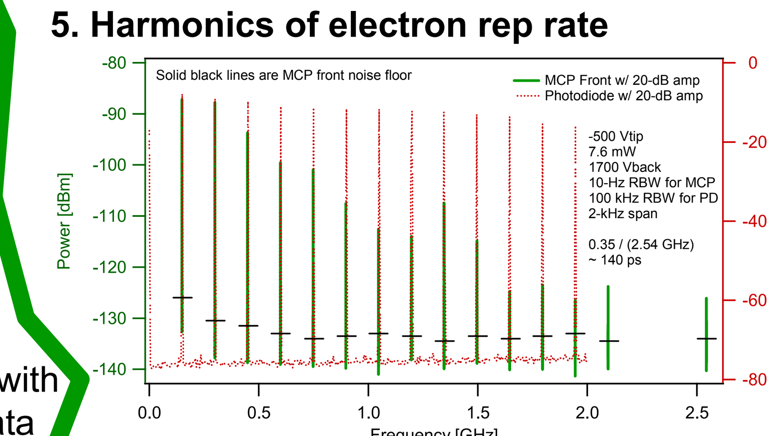


Hommelhoff et. al., PRL **97** (2006)

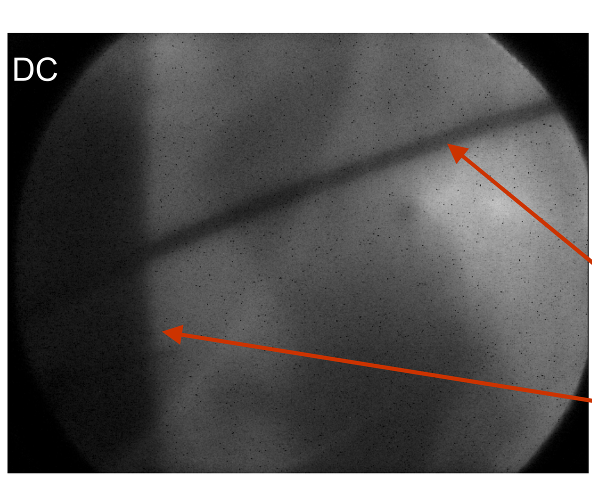


Numerical integration of Schrodinger eqn. agrees with nonlinearity vs. dc bias data

5. Harmonics of electron rep rate



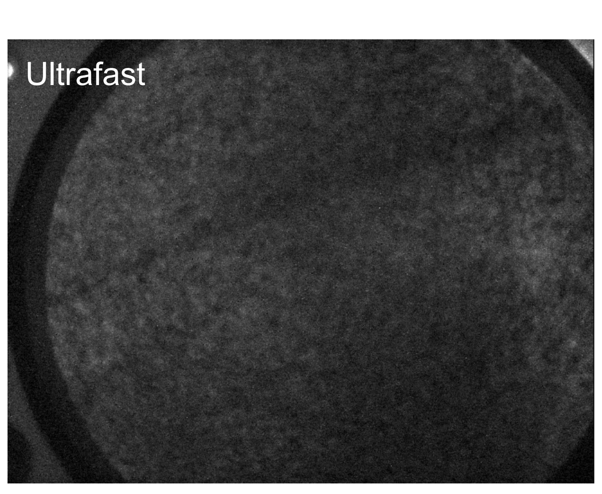
Initial Ultrafast X-Ray Results:



"Sharpness" of shadows used to determine x-ray spot size

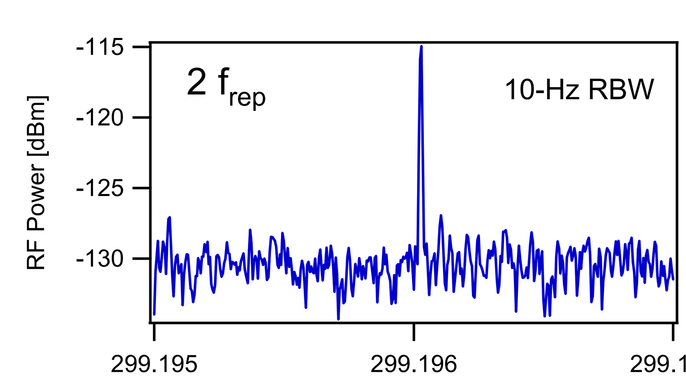
X-ray shadow of a thin wire in the chamber

X-ray shadow of the x-ray target's edge



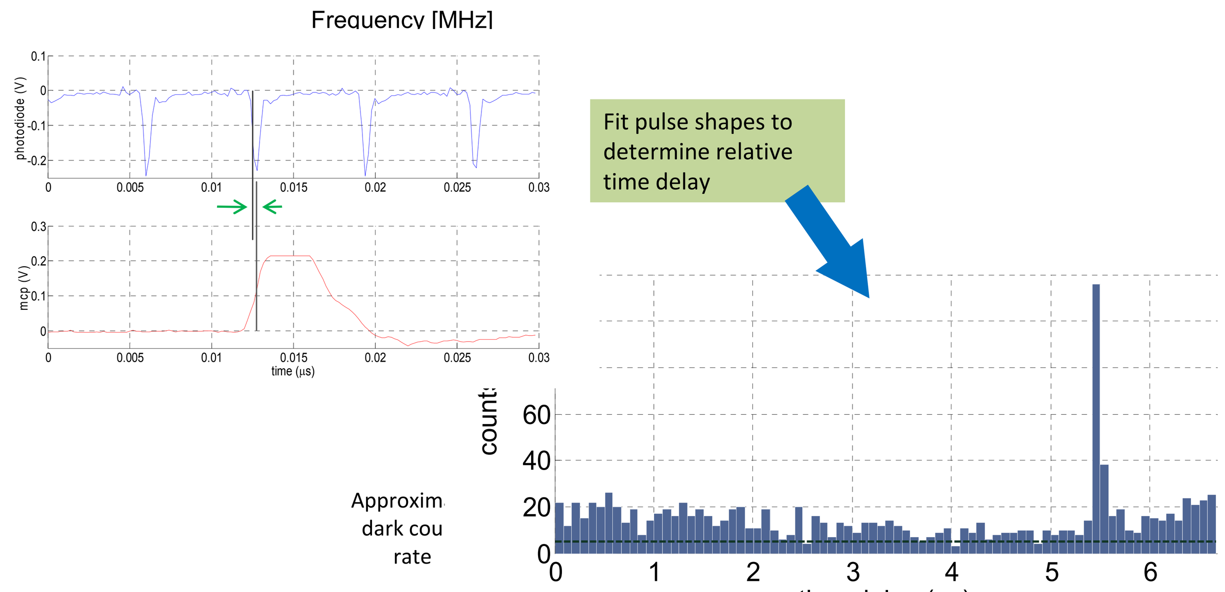
"Imaging" with ultrafast x-rays (grainy pattern from lower SNR due to low flux of fs x-rays)

Precision timing



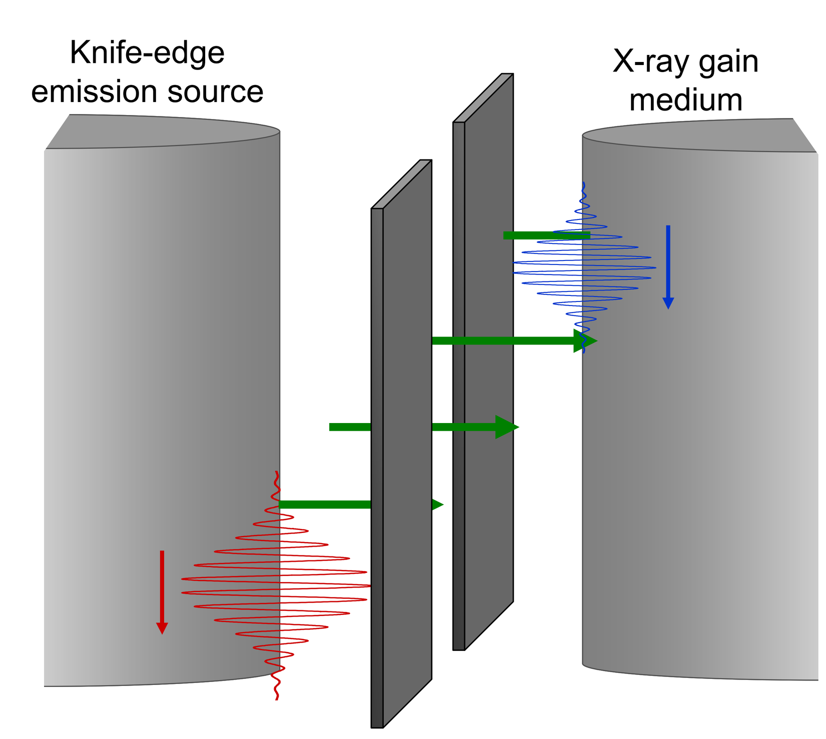
This x-ray signal was measured with only 20 x-rays per second detected.

Demonstrates that precise timing allows tiny signals to be recovered from noise.



Extension: Line Source, X-Ray Laser:

X-ray laser concept: traveling wave optical field emitter

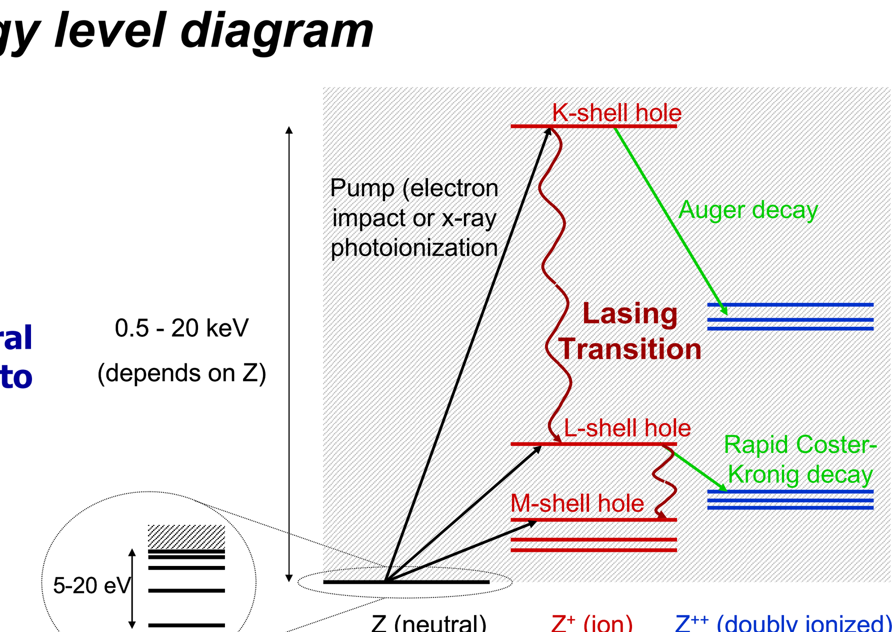


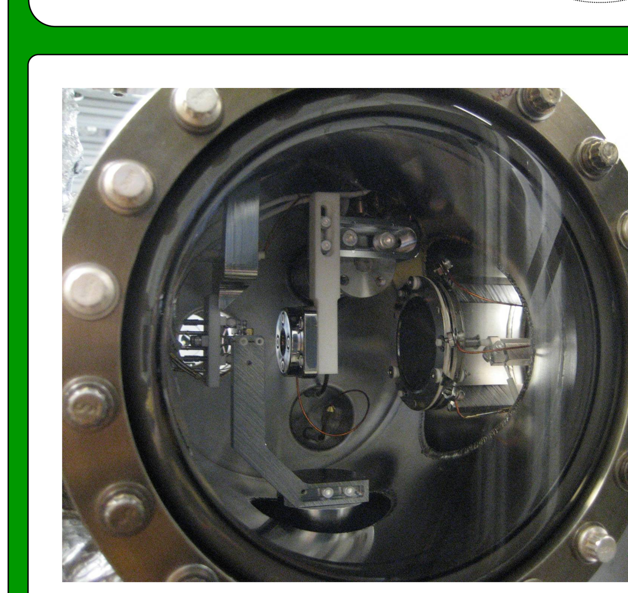
"Cylindrical" electron lens shown; small concentric cylinder geometry may help with space-charge difficulties

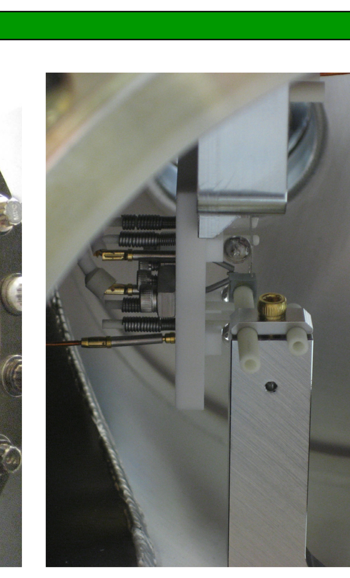
- **Would hugely improve brightness, directionality**
- **Ultrafast, coherent x-rays**
- **Huge peak brightness**
- **Tabletop source!**
- **Optical field emission is the enabling technology**
- **Requires 10^{11} A / cm^2 current density at gain medium for lasing**
- **Material damage is of concern**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

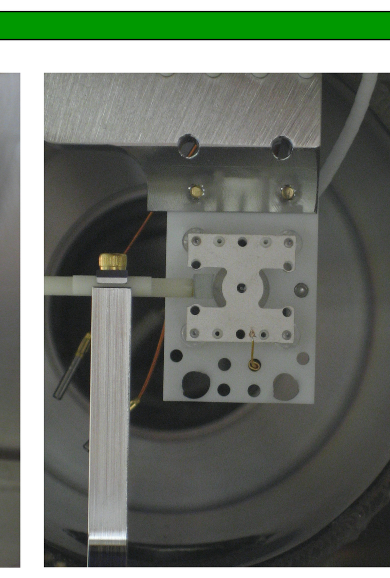
X-ray laser energy level diagram

- **Lasing occurs on inner-shell transitions**
- **Core holes have ~ several fs lifetimes due mainly to Auger decay**
- **Pumping must be fast!**





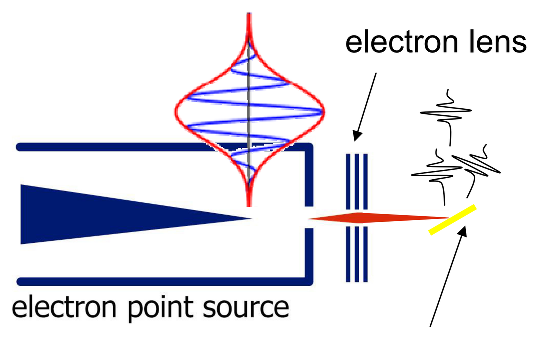




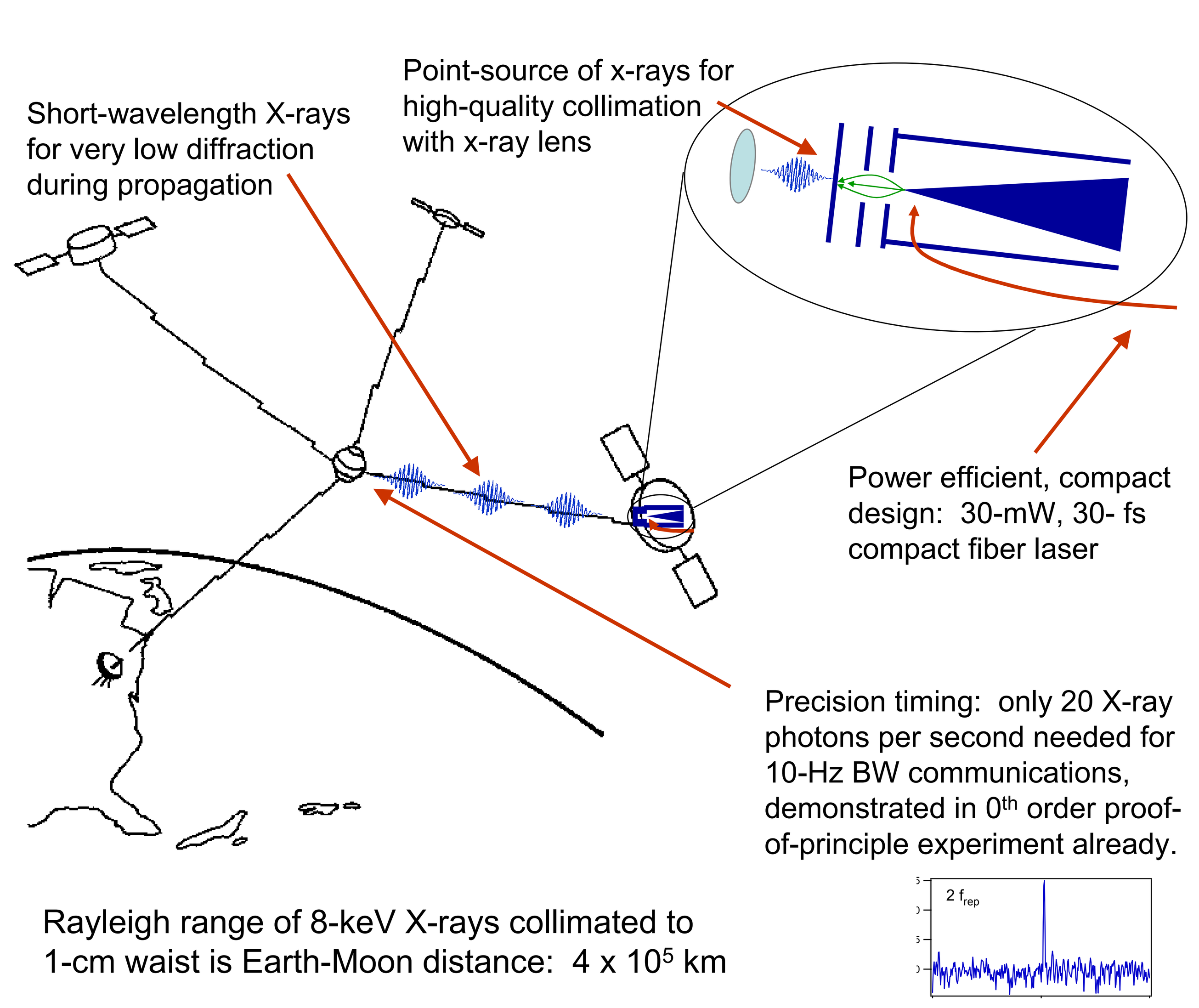
Space-Based X-Ray Communications Concept:

Ultrafast xray point-source

- Orders of magnitude advance in timing resolution over state-of-the-art.
- Extremely high peak brightness
- Tiny footprint (< 0.5 m²)



- 10^{10} A/cm² current densities have been demonstrated with field emission tips
- For 10-fs pulses, this peak current density yields ~ 100 – 1000 electrons
- At 1-GHz rep-rate, this yields 10^9 precision-timed x-rays per second



Rayleigh range of 8-keV X-rays collimated to 1-cm waist is Earth-Moon distance: 4 x 10^5 km