Femtosecond electron emission from ultra-high field laser illumination of nano-blade structures

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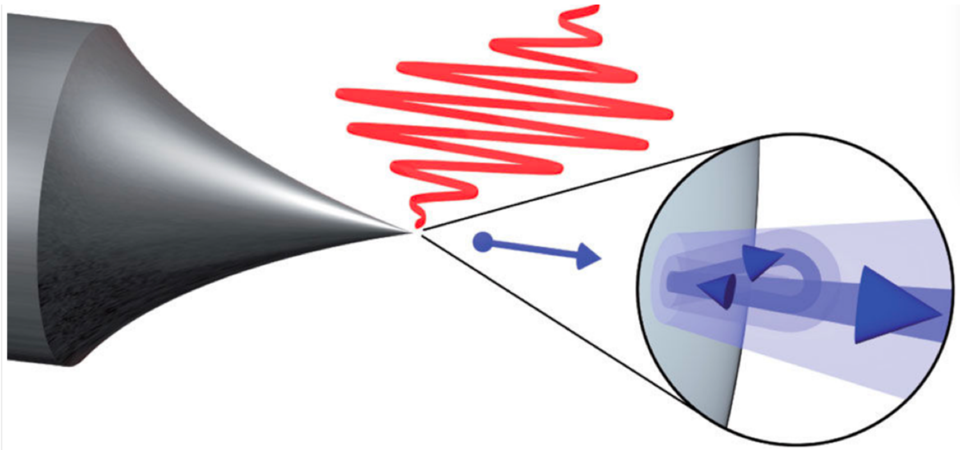
17 October 2018

P3 conference – Santa Fe, NM

Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center
NSF Award PHY-1549132

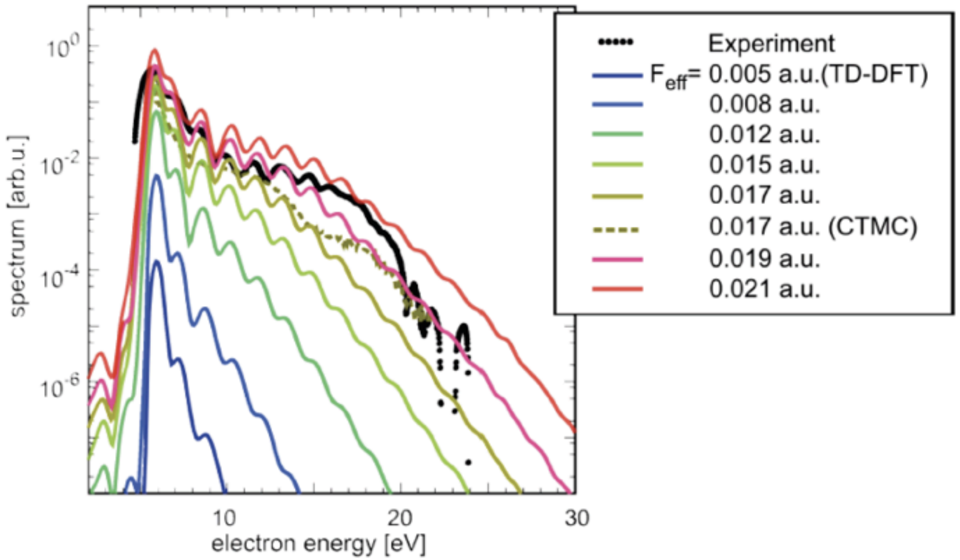
Historic background: nano-tip emission

- Nanotip emission experiments by Hommelhoff group
- High field (tens of GV/m) physics with field enhancement structure
- Electrons gated with few fs duration; tunneling and rescatttering



Field enhancement from tip in surface-laser interaction experiments

M. Kruger, et al. *New Journal of Physics* **14**, 085019 (2012).



Plateau in e- spectrum with rescatter structure
Simulations approximate stucture

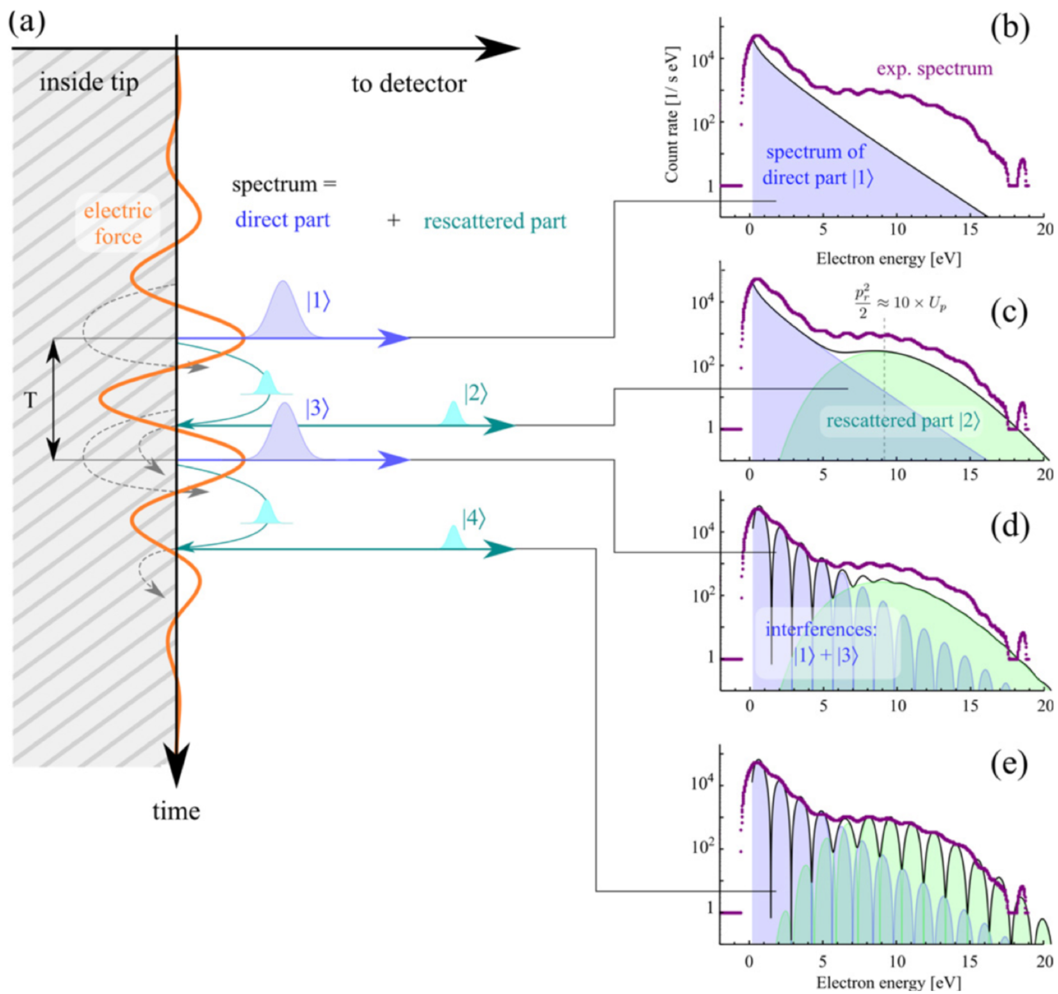
G. Wachter, et al., Phys. Rev. B 035402 (2012)

Model for electron spectrum through rescattering process

- Tunneling followed by successive rescattering at surface
- Timing set by laser field
- Quantum interference displayed, with $\hbar\omega$ separation
- Maximum energy of electrons scaled to ponderomotive energy $U_{e-} \simeq 10U_p$ with

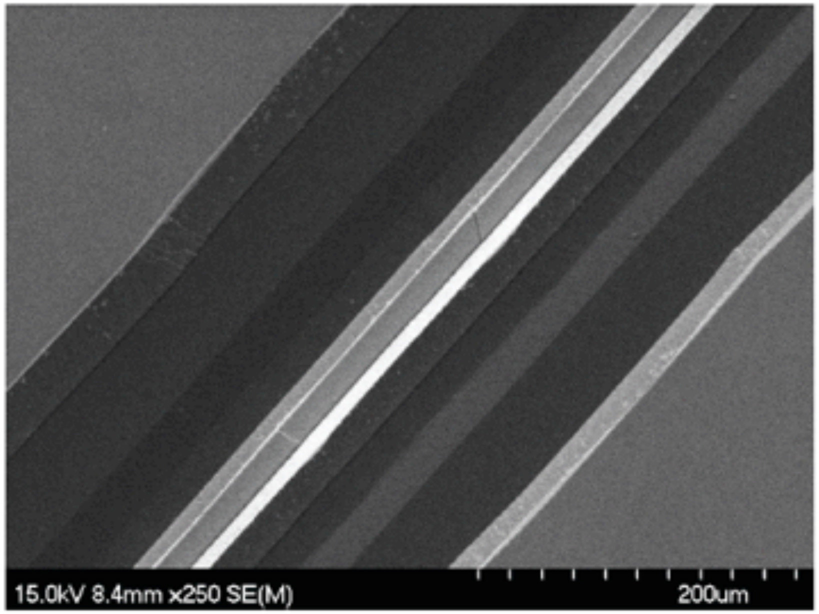
$$U_p = \frac{1}{m_e c^2}\left(\frac{eE_0\lambda}{4\pi}\right)^2$$

- Favors long λ, large field E_0

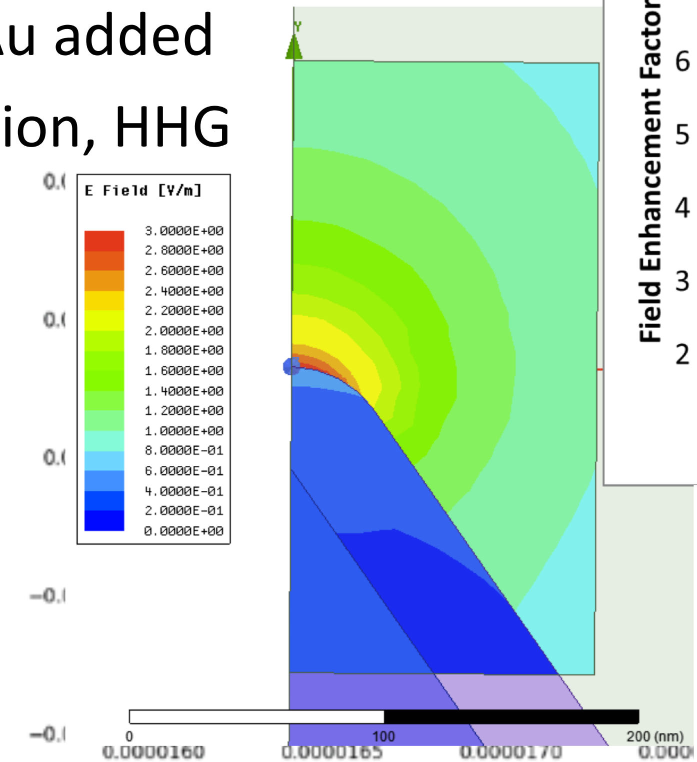


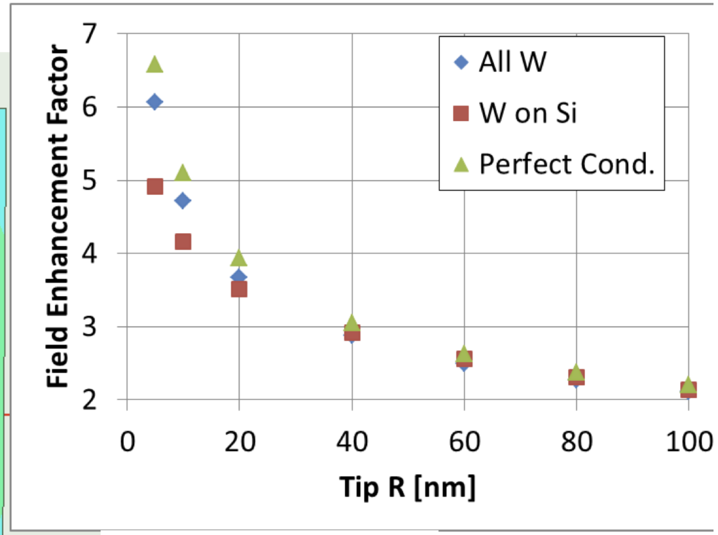
Realizing a more robust emitter: nano-blade structures

- Much higher fields; heating mitigation
- Silicon substrate (etched), W, Au added
- Geometry for electron production, HHG



Micrograph of etched Si blades
(without W layer)

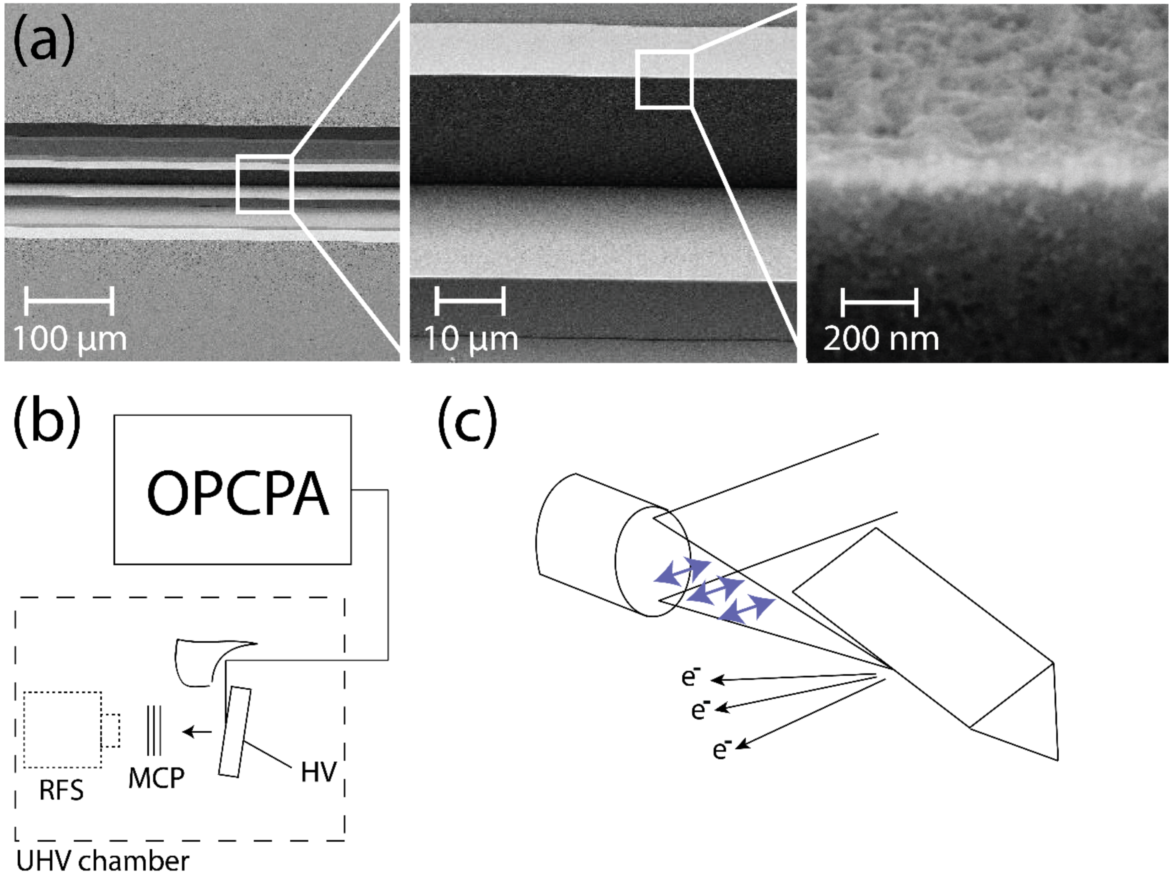




Field enhancement simulation with HFSS
- Plasmonic effects notable

Initial W Blade Rescattering Experiments

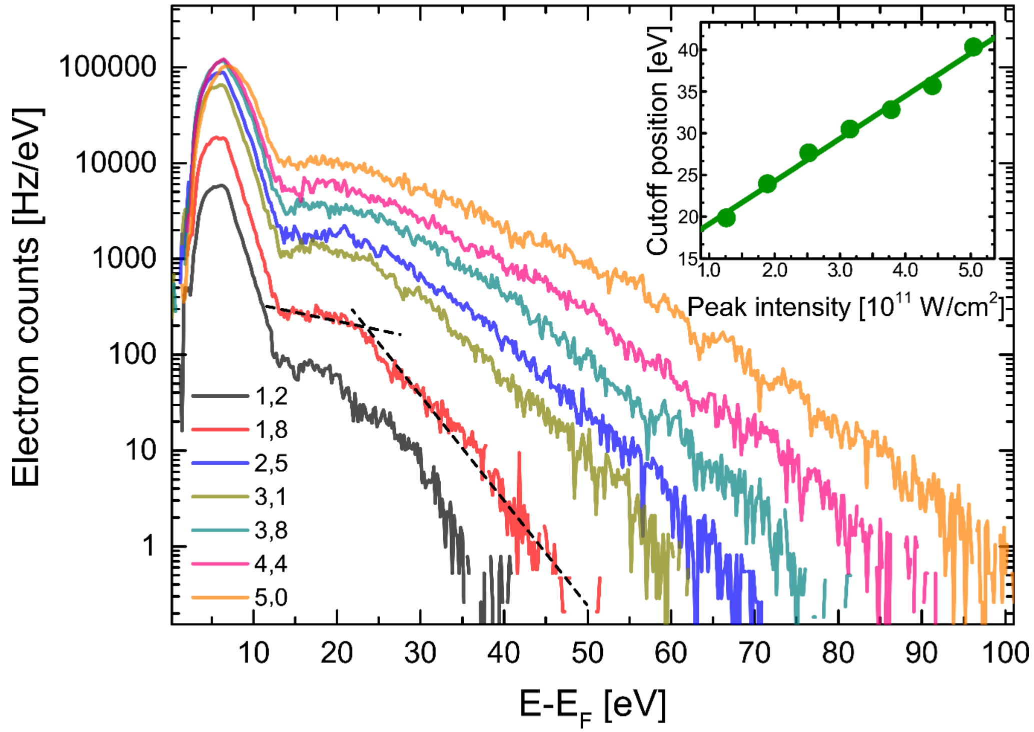
Blade geometry and optical setup



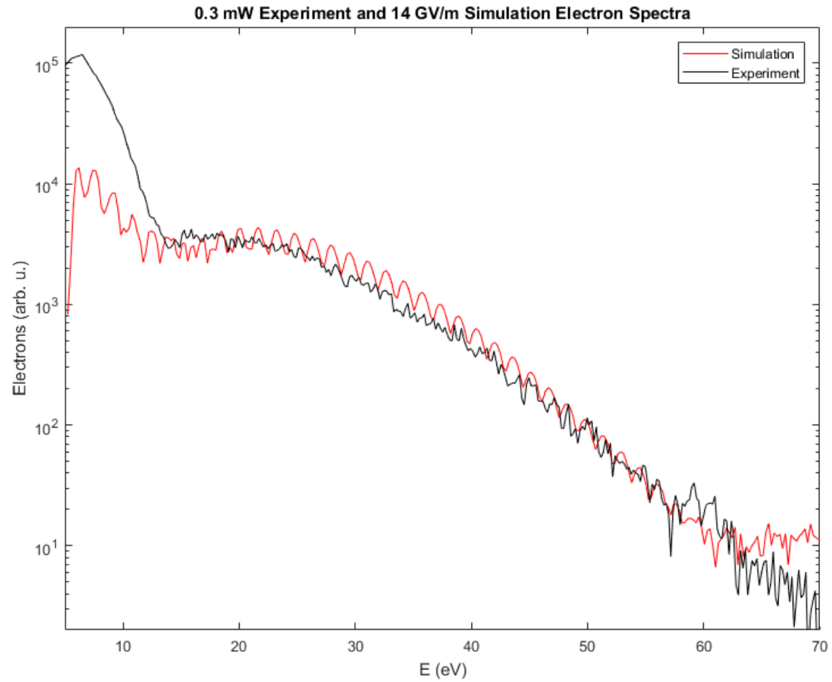
Note structure at
20 nm level

Tungsten Blade: Rescattering data

Electron energy spectra



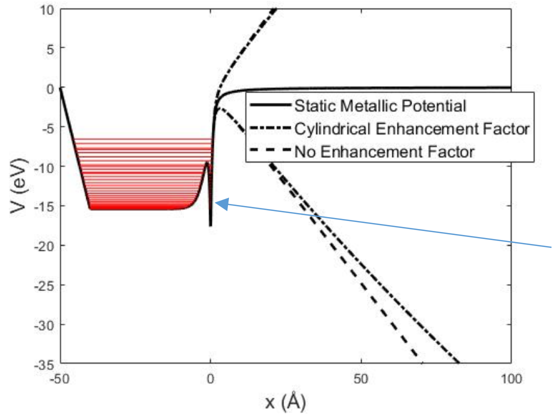
Emergence of rescattering plateau
Familiar from nanotips!



Comparison with UCLA TDSE model (J. Mann)

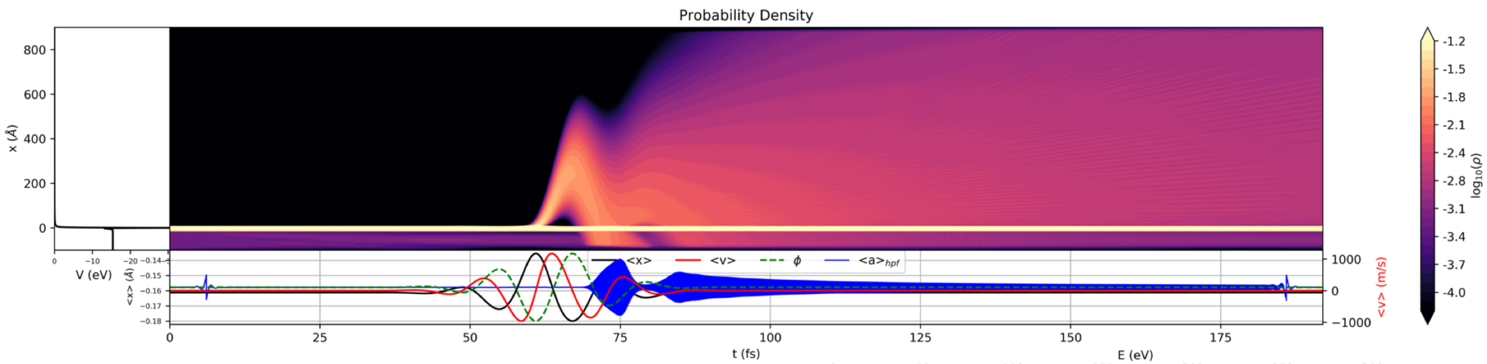
Simulation approach

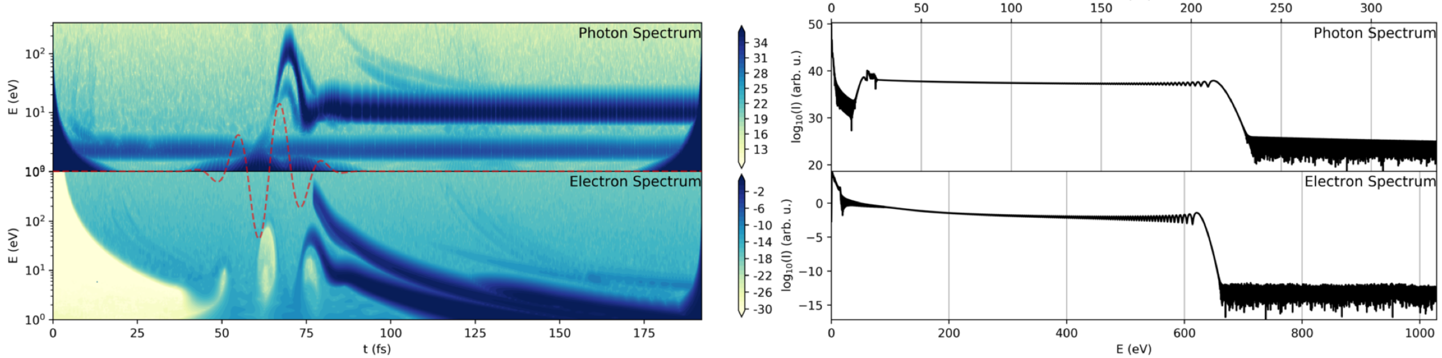
- Potential: Jellium/work function, image charges with shielded core potential in 1-D
  - Planar average over distributed $1/r$ potentials
  - Sequence of atomic layers for higher energy
  - Now implementing SC and field penetration



$$V(z)=\frac{Ze^2}{2\varepsilon_0 d^2}\sqrt{\frac{d^2}{\pi}+z^2}-|z|$$

λ = 3900 nm, τ = 8 fs, E_{max} = 20 GVm^{-1}, $\gamma_{Keldysh}$ = 0.202923, U_p = 75.2836 eV, dt = 7.73693e-05 fs, dx = 0.0471405 Å





20 GV/m peak field (conservative), with 3.9 um laser. Comparison with previous experiments…

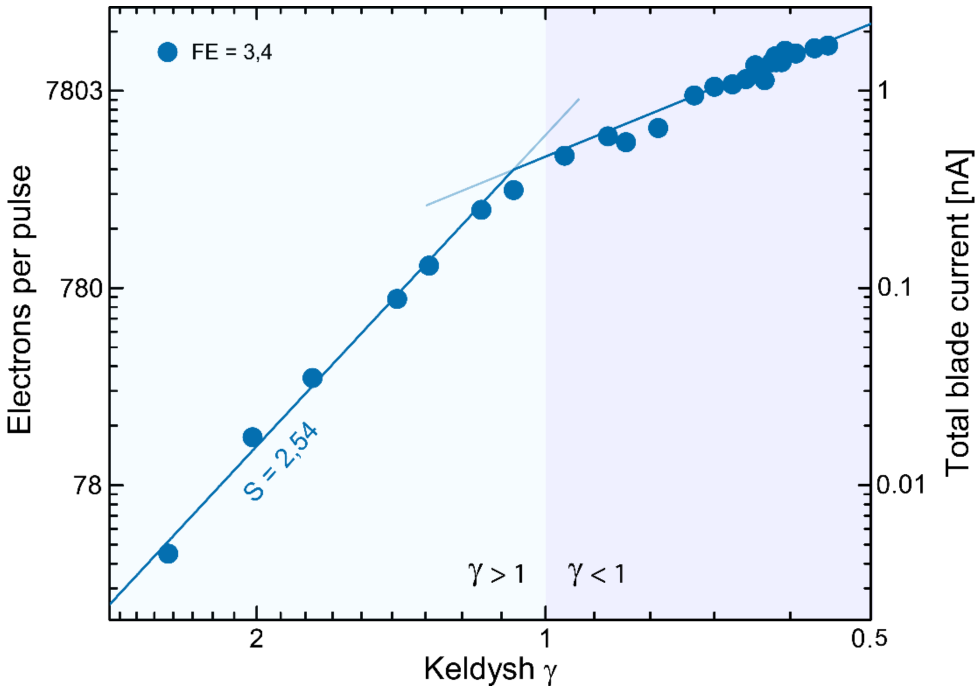
Using 10 um laser to reach *m*=100,000 – 1 Angstrom X-rays – computationally intensive

Cut-off for photons at 3.17 U_p (225 eV)
Cut-off for electrons ~10U_p

New tool for high field emission

Tungsten Blade: Rescattering data

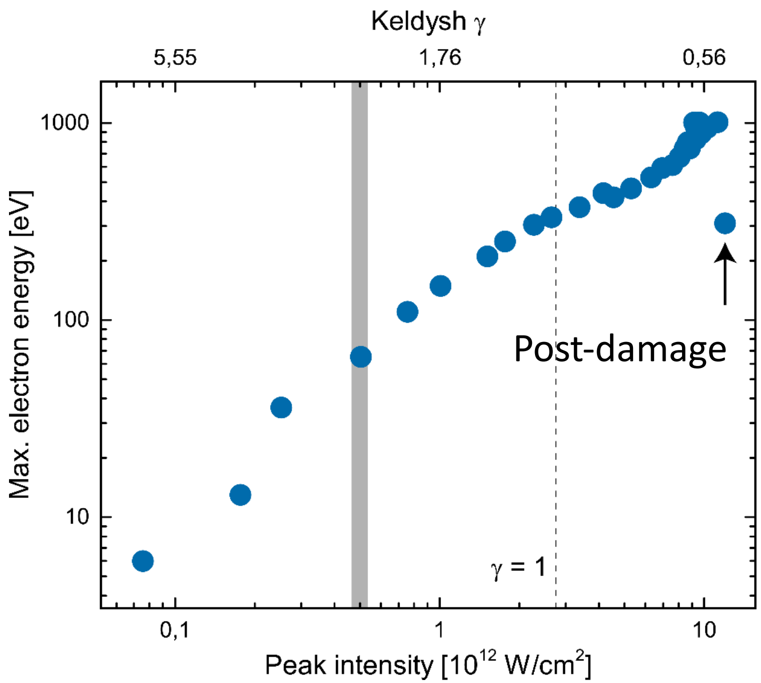
Total blade emission current



- Kink in total electron emission (change of slope) near $\gamma = 1$
  - Transition between multiphoton (MP) and tunnel regime, high absolute yield
  - **Onset of space charge *Q~E²*** (ponderomotive force for escape)?
  - More than 1E4 e-s/pulse for highest intensities (now 1E6)

Tungsten Blade: Rescattering data

High electron energies

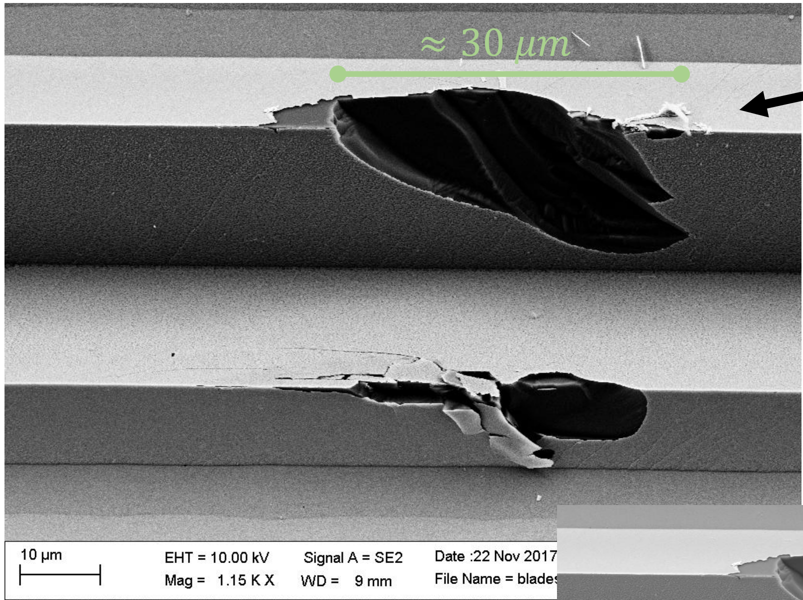


1 keV maximum electrons

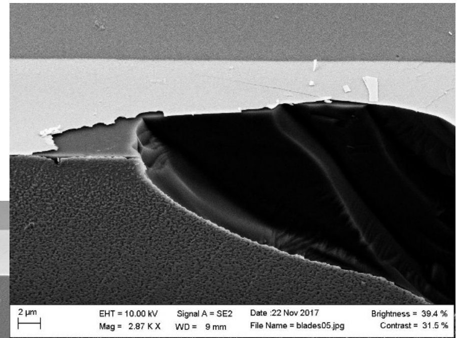
- Spectrometer filter voltage set such that electron count rate ≈ 100 counts/s
- Highest measured electron energy 1000 eV at 10^{13} W/cm^2
- Electron energy at $0.5 * 10^{12}$ W/cm ^{2}(grey area) matches count rate / energy in previous spectrum

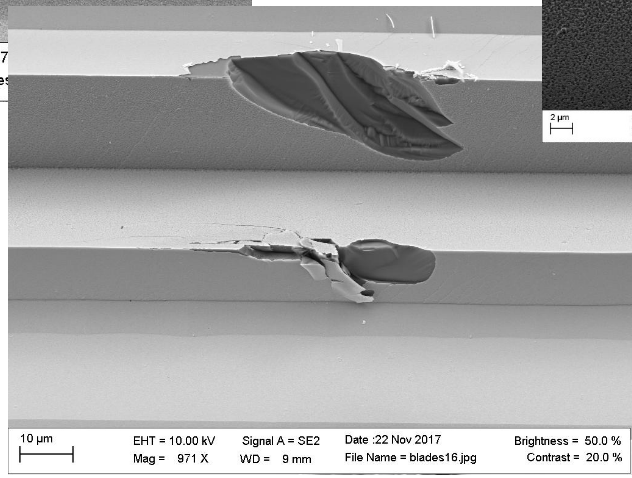
Tungsten Blade: Rescattering data

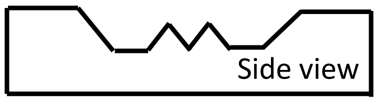
SEM inspection after experiments



- Damage due to focused 200 mW average power
- Damaged area restricted to highest intensity region
  → Elongated focal spot

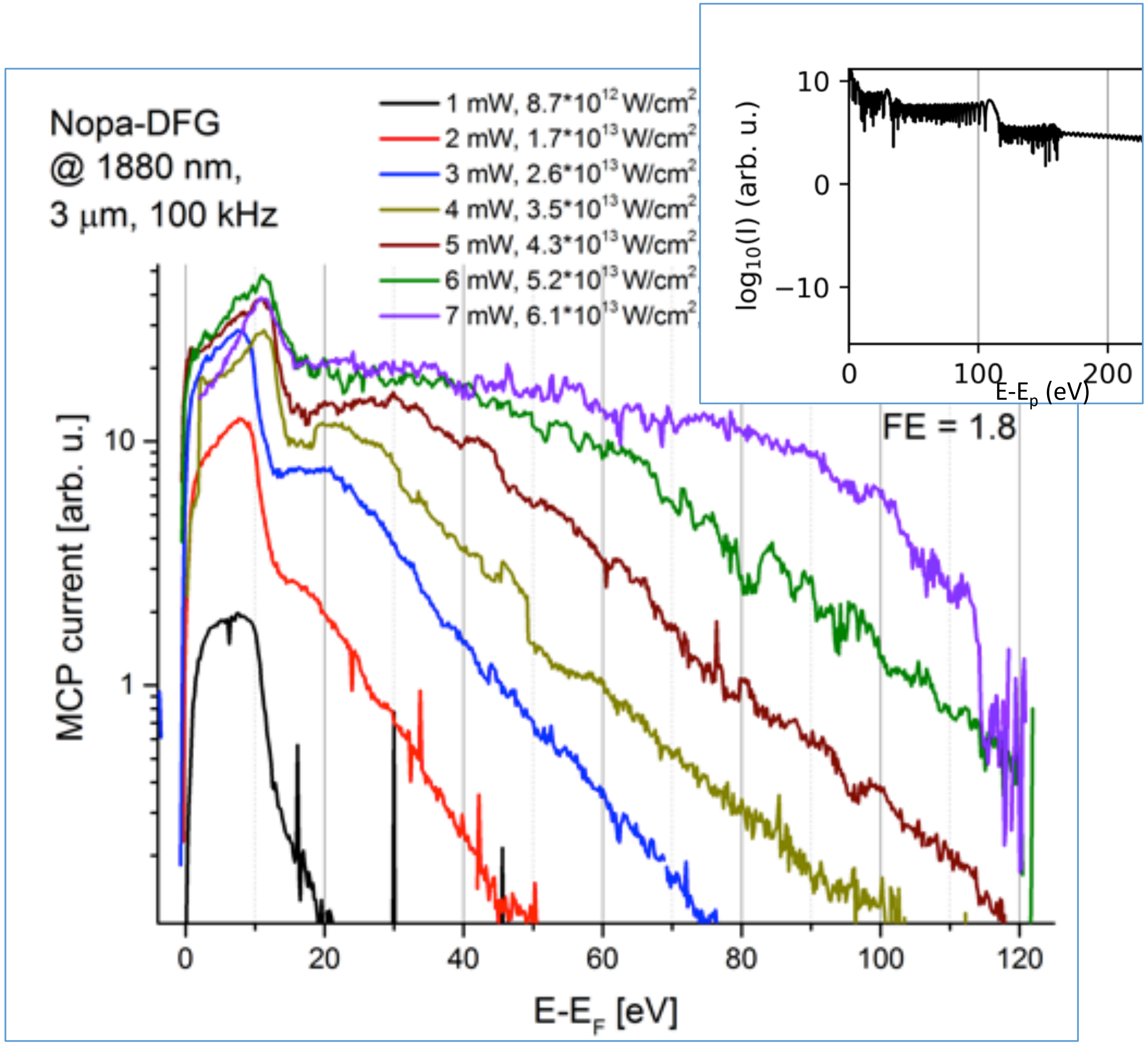




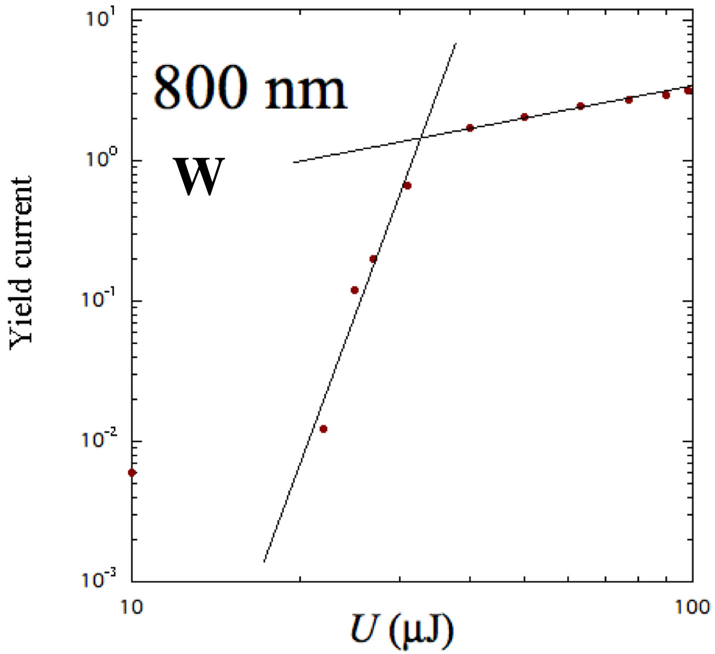


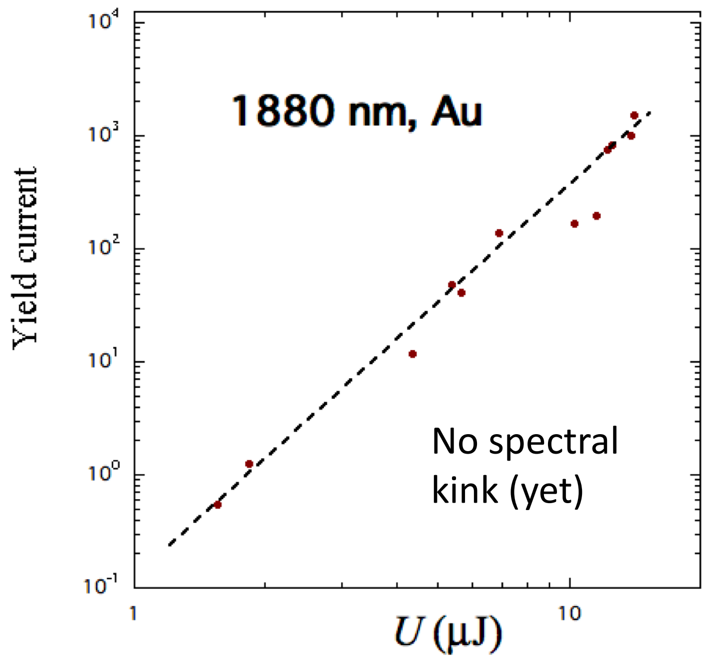
Longer wavelength blade emission tests

- High fields, λ_L=1.88 μm
- Definitive plateau to >80 eV
- Further studies underway
  - Comparing nanotips to blades
  - Push field limits
  - Work now at UCLA



Recent progress at UCLA

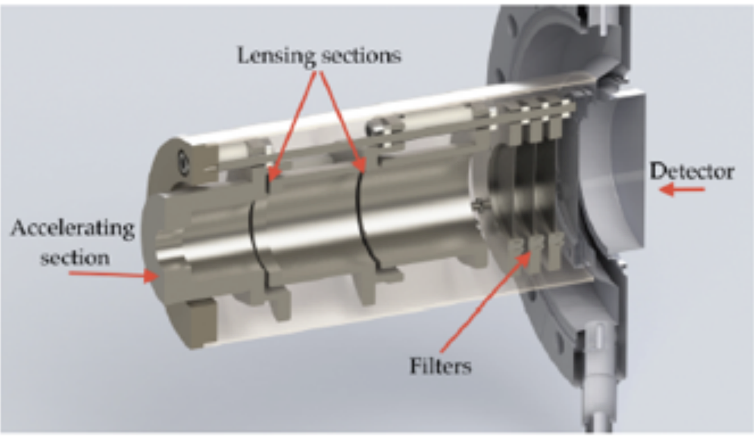




- Many orders of magnitude more laser energy, electron yield
- 40 fsec, not 8 fsec. Tunable wavelength
- W/800 nm data familiar. Au at 1880 nm has *much* higher yield

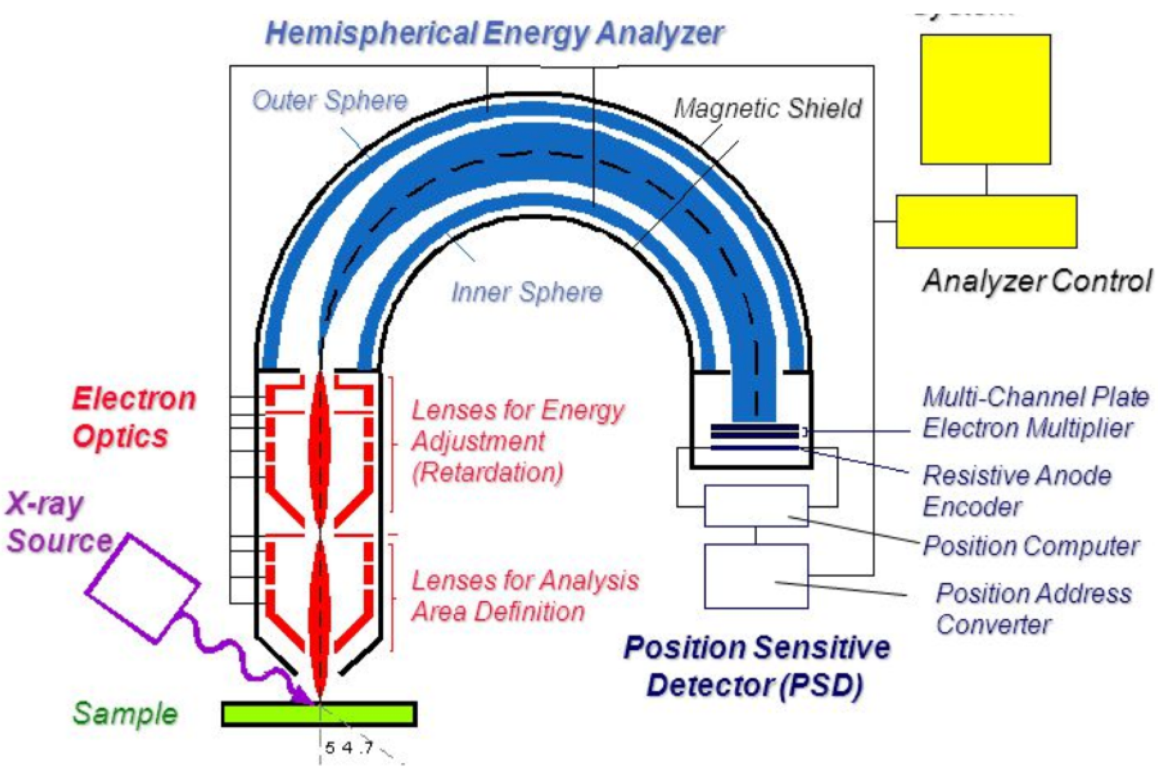
Hemispherical electron spectrometer

- Go to tunable imaging spectrometer
- Hemispherical electrostatic equipotential
- Create separate energy beams for characterization
- Now under construction at UCLA



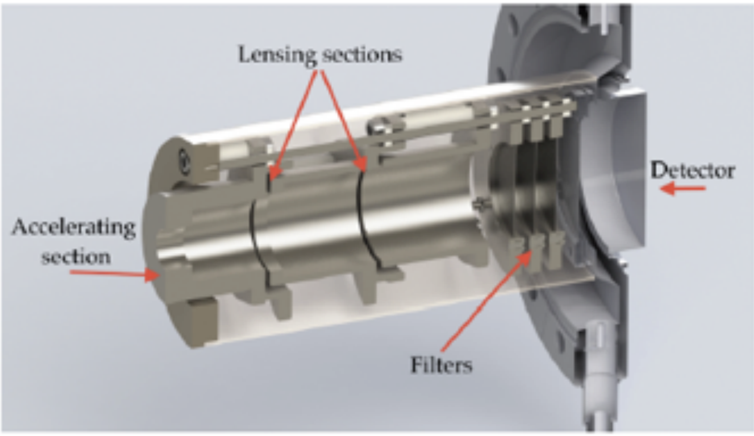
Present spectrometer

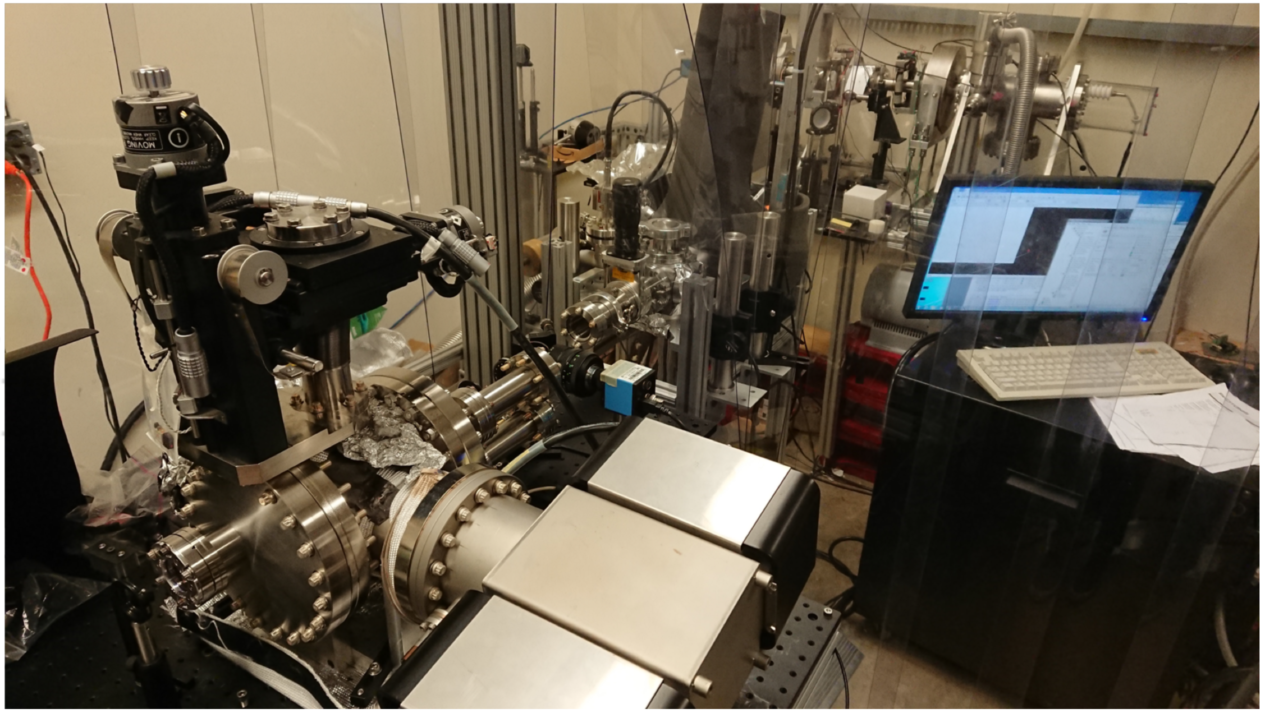
Schematic of imaging electron spectrometer



UCLA Lab Development and Experiments

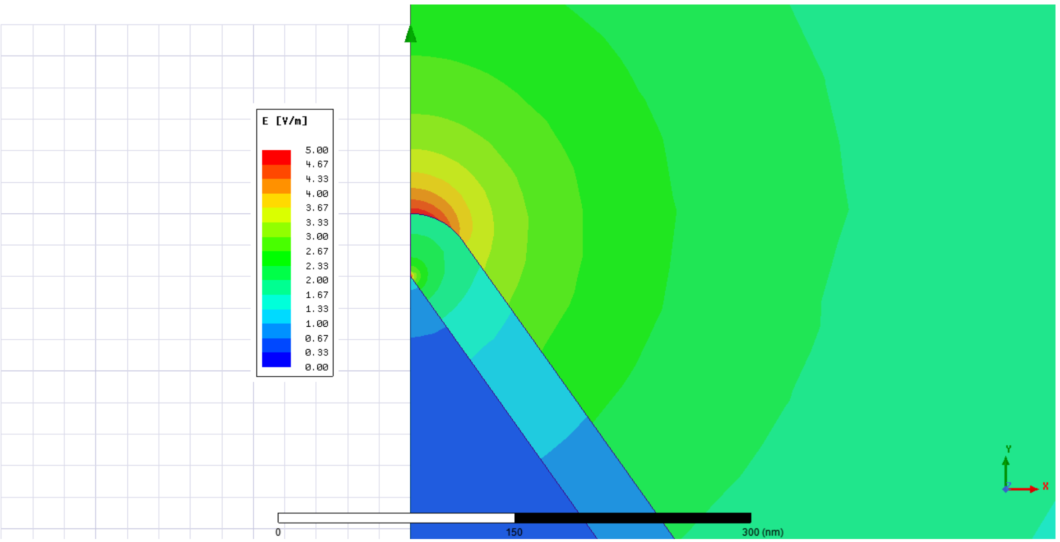
- Very large laser pulse energy (to 5 mJ), 15 fs, 800 nm Astrella system
  - Long Rayleigh range, multiple blade illumination
  - Palitra OPA allows to reach 10 um light and beyond
- High resolution e- and photon (to EUV) spectrometers
  - 1st experiments now



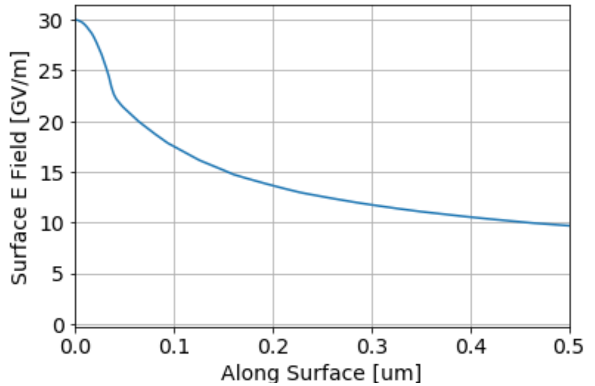


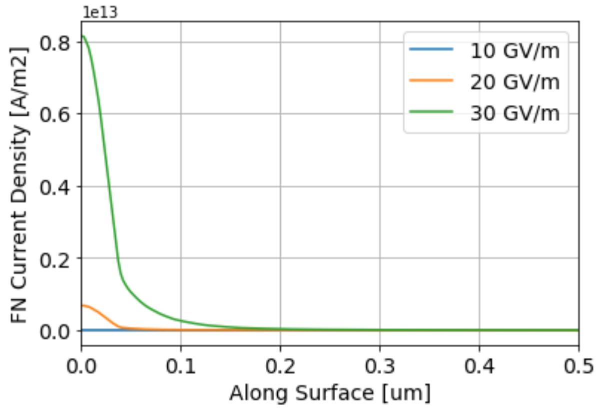
Blades as asymmetric emittance injector

- Applications: linear collider, dielectric laser accelerator
- Playground for emission – high fields, small dimensions, launching with **large** directed energy (beat Child-Langmuir-like scaling)



Field environment, blade cross-sectrion



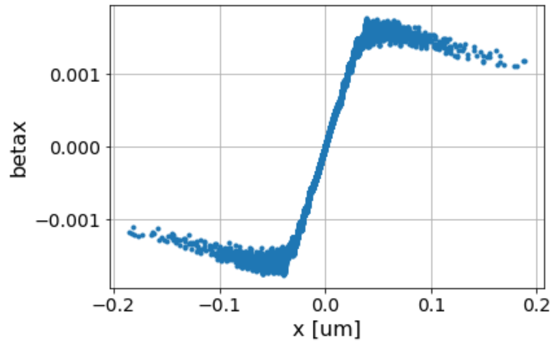


Dynamics with GPT

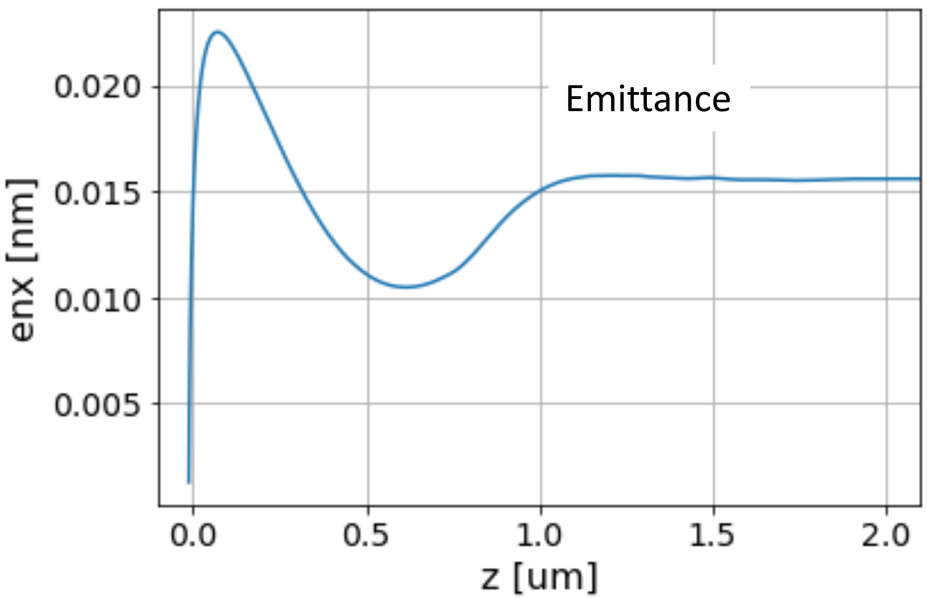
Emission:
- **800 nm, half cycle, 30 GV/m**

Fowler-Nordheim current
- **DC extraction field 100 MV/m**
- **No laser interaction dynamics**
- **Emittance promising**
  - **Consistent with source size and *T***

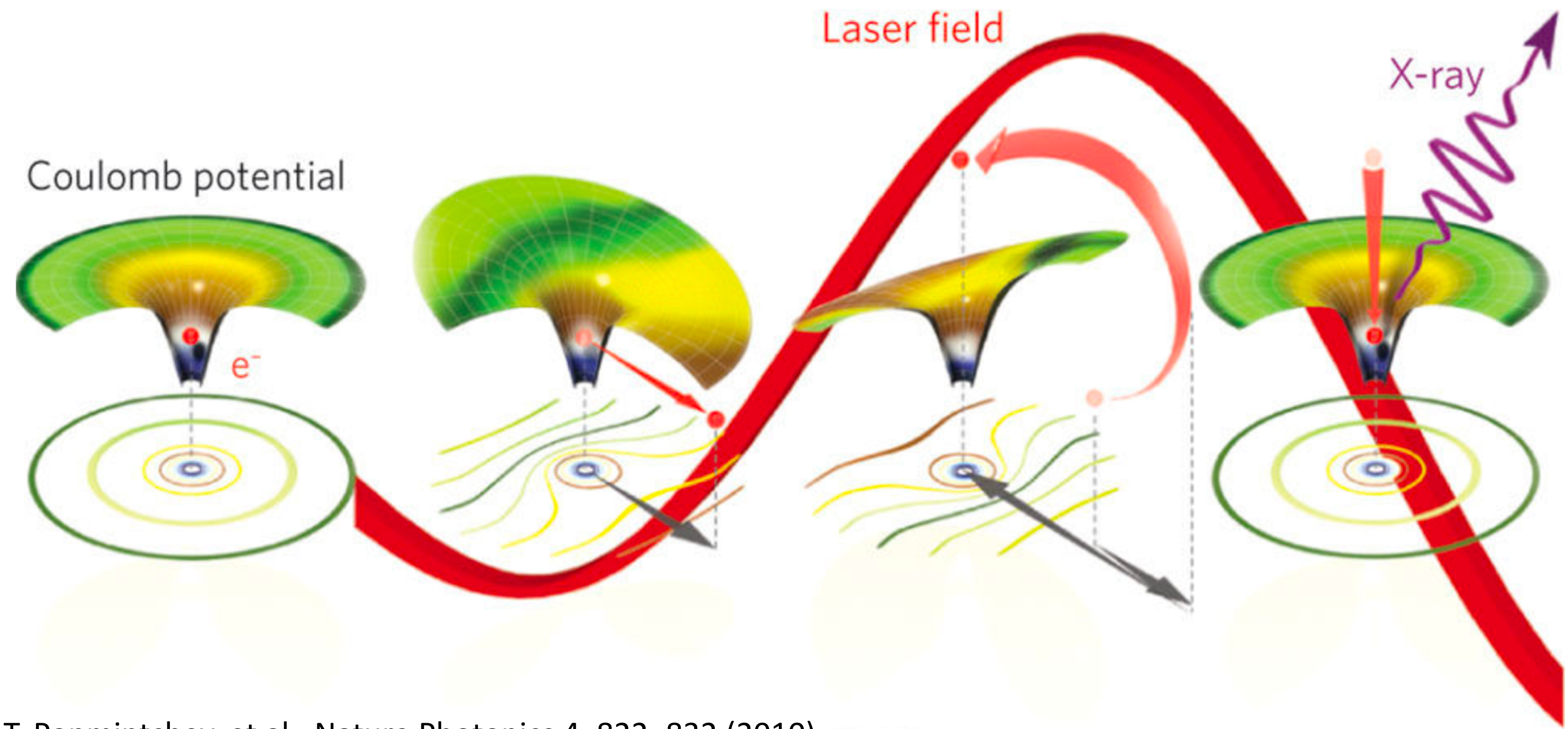
Next: embed in RF photoinjector
- **Hide large energy spread**
- **Preserve time structure**



Phase space



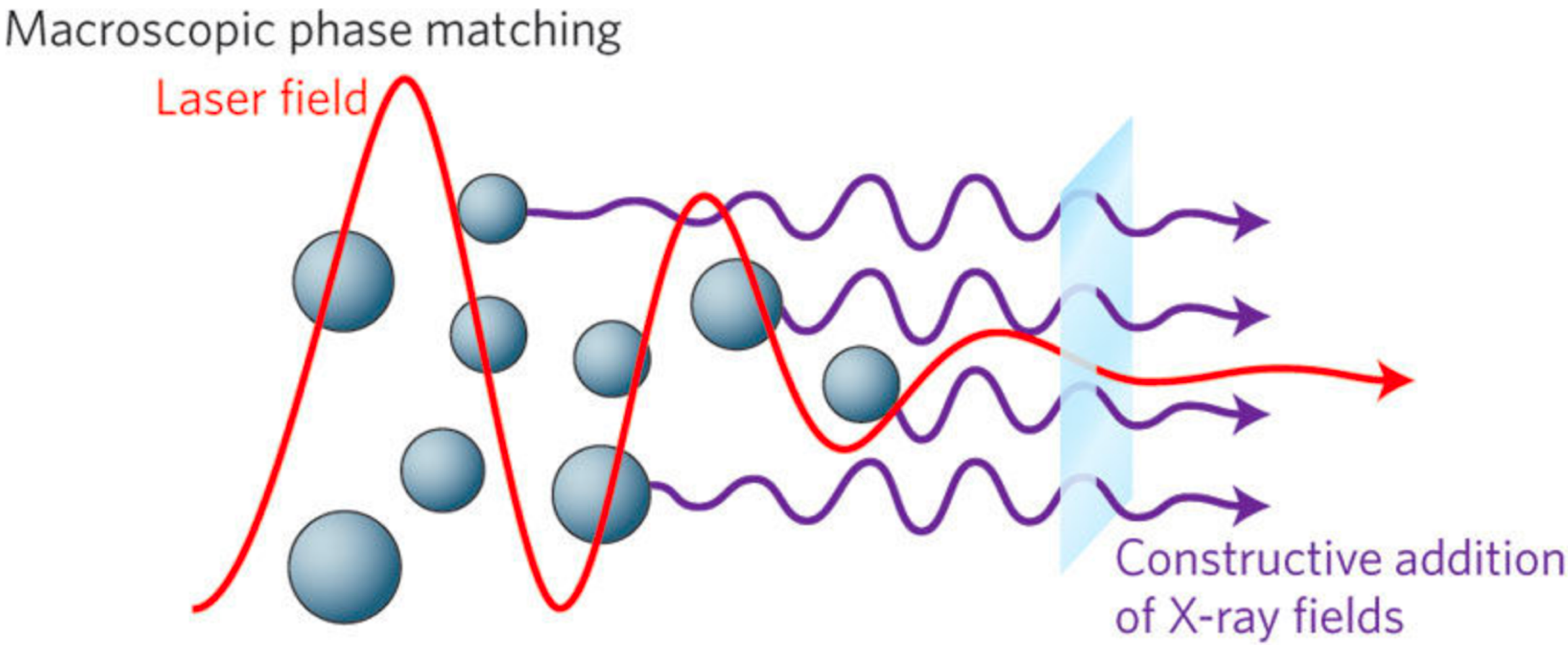
Rescattering: basis ofhigh harmonic generation, HHG
T*hree-step model for electron, radiation dynamics*



T. Popmintchev, et al., Nature Photonics 4, 822–832 (2010)

Harmonic train (x-rays) produced on recombination

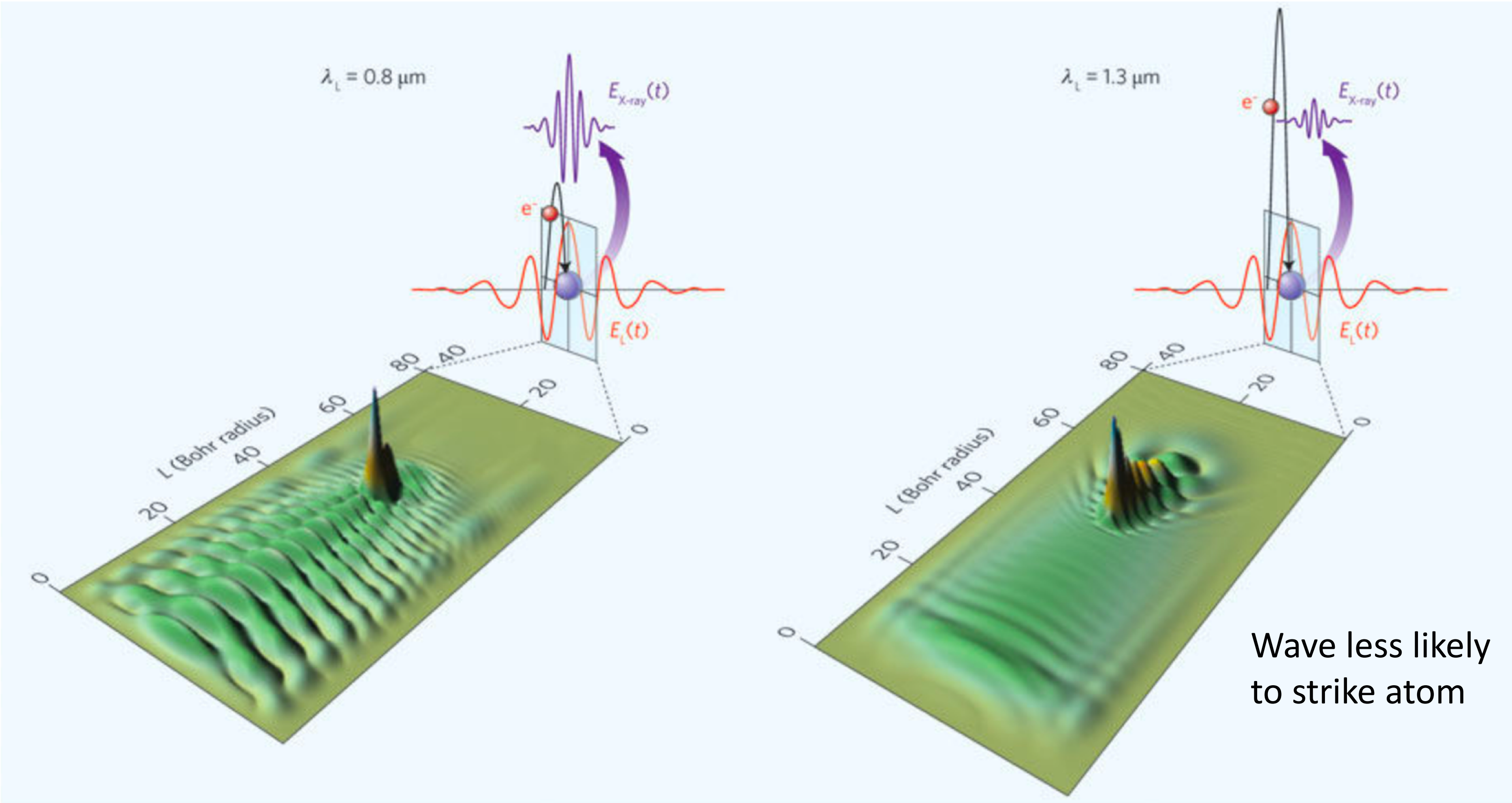
Phase matching and coherence



Laser and harmonics have ~same phase velocity. Complex solutions

Long λ_L use limited by wave-packet diffusion

Power efficiency $P \sim \lambda_L^{-6}$



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Spectral characteristics

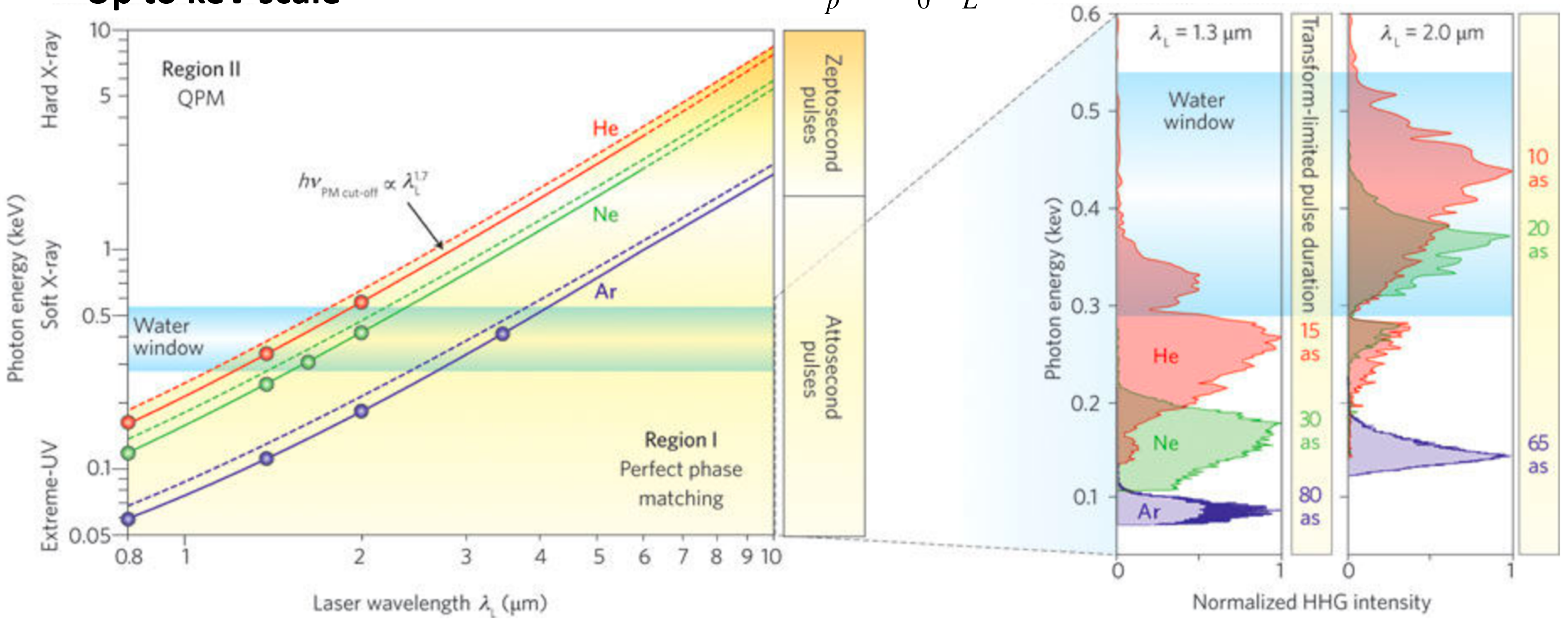
UCLA

Harmonics up to frequency consistent with available energy on recombination

- **Up to keV scale**

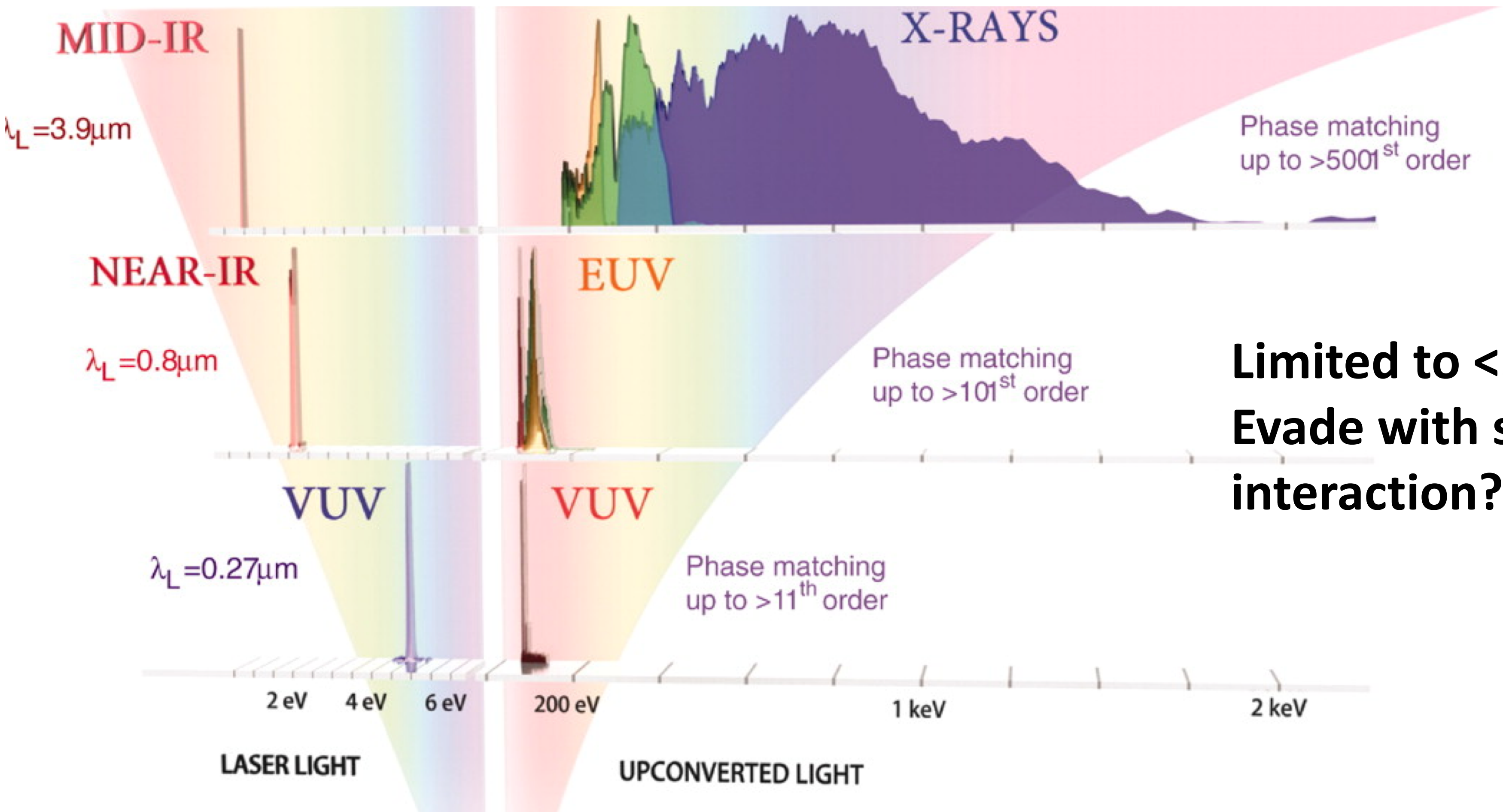
$$\hbar\omega_{\max} = 3.17U_p + W,$$

$$U_p \sim E_0^2 \lambda_L^2$$



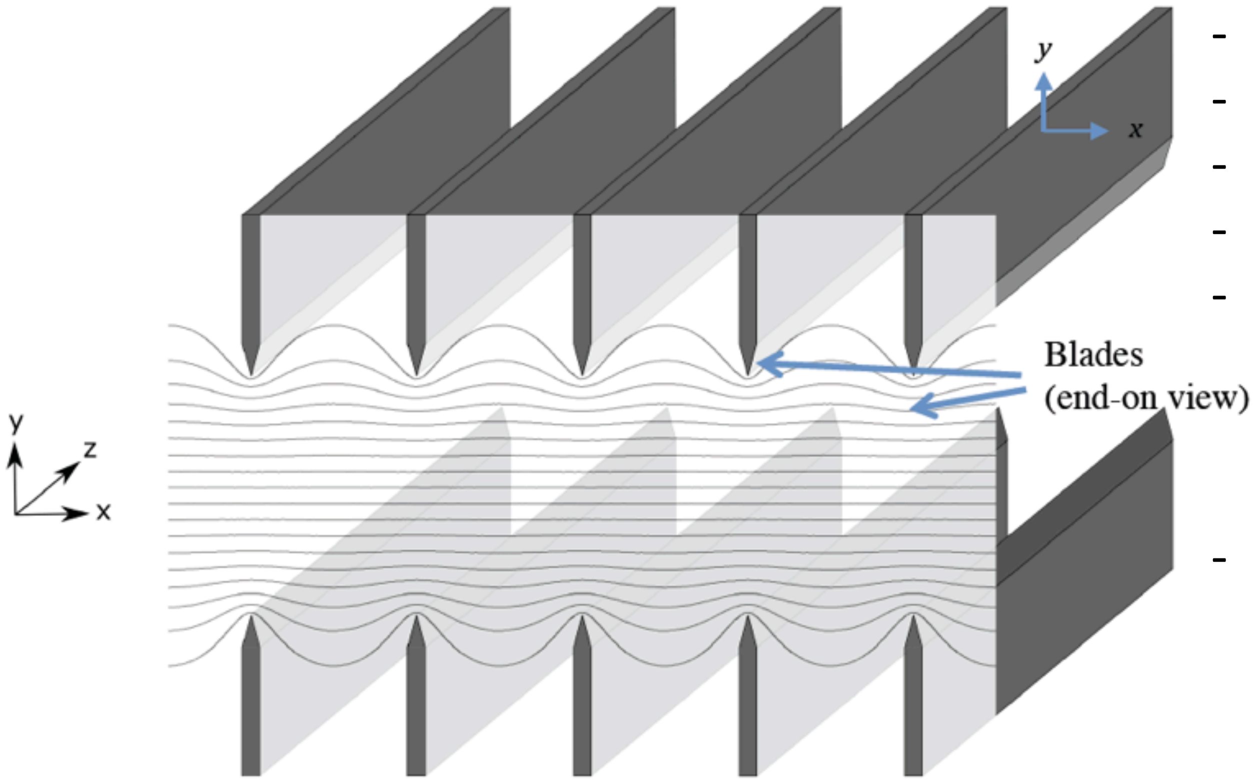
T. Popmintchev, et al., Nature Photonics 4, 822–832 (2010)

Record 5000th harmonic with 3.9 μm laser



Limited to <5 um
Evade with surface interaction?

Proposed blade waveguide geometry

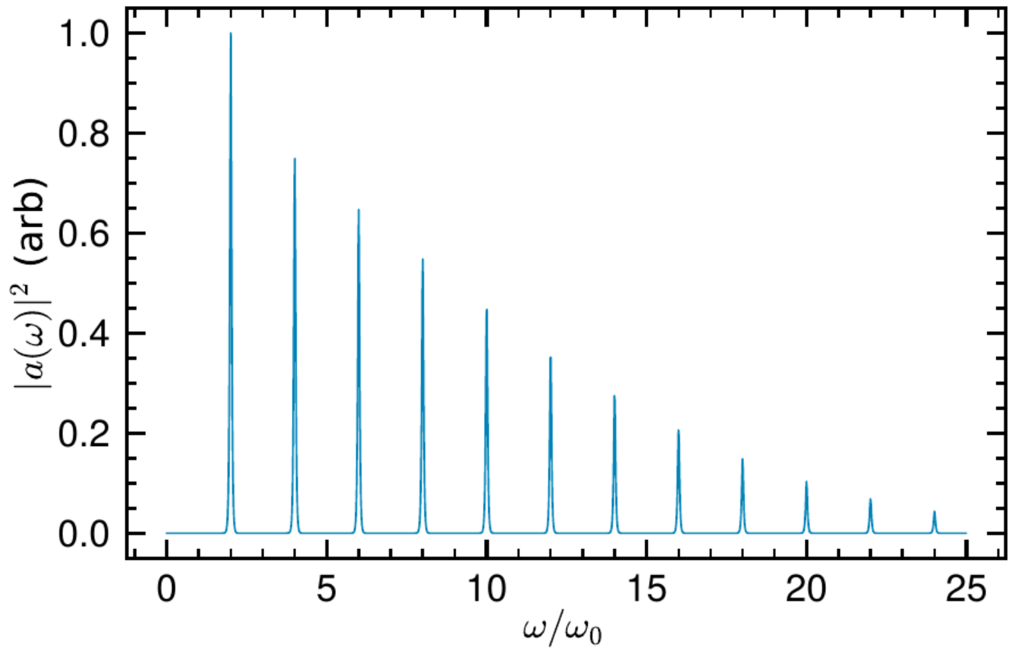


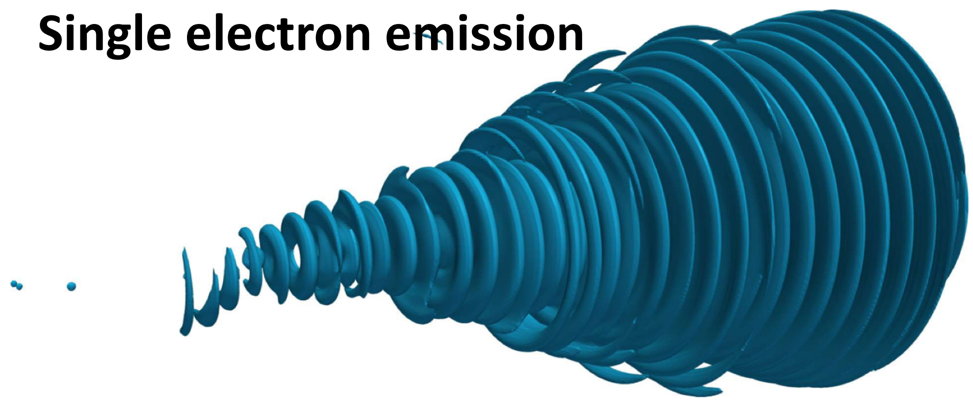
- Opposed arrays of nano-blades
- TEM propagation, v_ϕ=c in PEC case
- Large laser mode area, large laser *U*
- Parallel production of HHG
- HHG serves as probe for surface physics
  - Reconstructed surfaces
  - (De)localization
  - Plasmonic response
- New potential, extend to *m*=100,000
  - 10 um drive -> 1 Angstrom light!
  - Limit laser λ 0.5-cycle
  - Breakdown field limited

With higher efficiency/atom w.r.t. gas HHG, multiple blades we can have several orders of magnitude higher X-ray flux

Estimating the photon production

- Use electron dynamics/acceleration in many emitter simulation
  - TDSE calculation as kernel
- First results in hand for new experiments
- Total flux more than competitive with capillary HHG





Conclusions

- Robust emission observed from nano-blades (extruded nano-tips)
- Few fsec beams, very high brightness (already produced ~2E16 A/(m-rad)?)
- Promising asymmetric emittance source in new regime
- High yield, but broad energy spectrum
- Basis for extending HHG sources to Angstrom
- Rich physics to examine with electron and photon probes
  - Reconstructed surfaces
  - Localization and coherence
  - Tunneling times
- More sophisticated computational models wanted, including 3D effects