Teravolt-per-meter plasma wakefields from low-charge, femtosecond electron beams

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Brightness Begets Brightness: Electrons and Photons

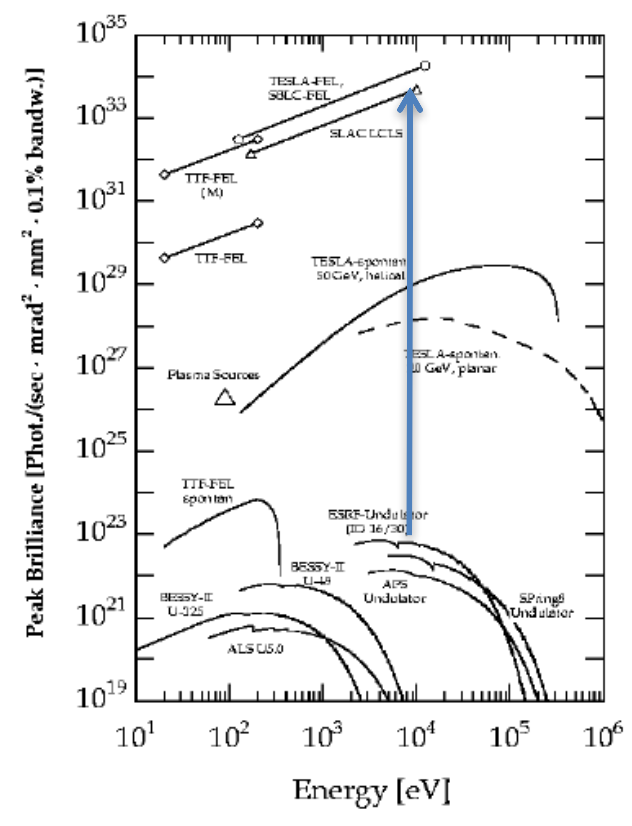
- Light source revolution due to e- beam improvements

$$B_e = \frac{2I}{\varepsilon_n^2} \rightarrow 2\times 10^{14}\ \text{A/m}^2$$

- Two orders of magnitude produce qualitatively new *light source*, the X-ray Free-electron Laser
  - Intense cold beam; instability

$$E_{rad} \propto \exp\left(z/L_g\right);\ L_g \propto B_e^{-1/3}$$

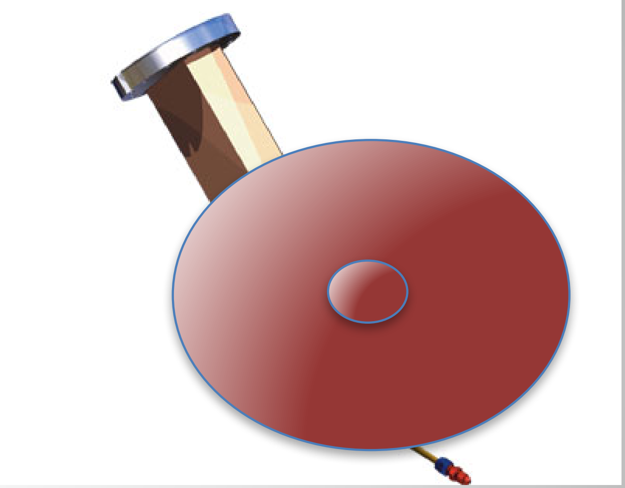
  - 8 orders of magnitude photon brightness
- For needed e-beam, must compress to fs scale
- Ultra-bright, Å, coherent, fsec light source
  - X-ray FEL: many orders of magnitude leap forward



Ultra-short XFEL pulses: motivation

- Tool at atomic *electron* spatio-temporal scales
  - Angstroms-nanometers (~Bohr radius)
  - **Femtoseconds** (e^- motion, Bohr period; femto-chemistry, etc.)
- 100 fs accessible with standard approaches
- Promising path: ultra-short, low *Q* electron beam
  - Myriad of advantages in FEL *and* beam physics
    - Mitigate collective effects dramatically
  - Robust in application: XFEL, coherent optical/IR source
- Can also use microbunching…
- ***Spin-off*** **to ultra-high field PWFA!**

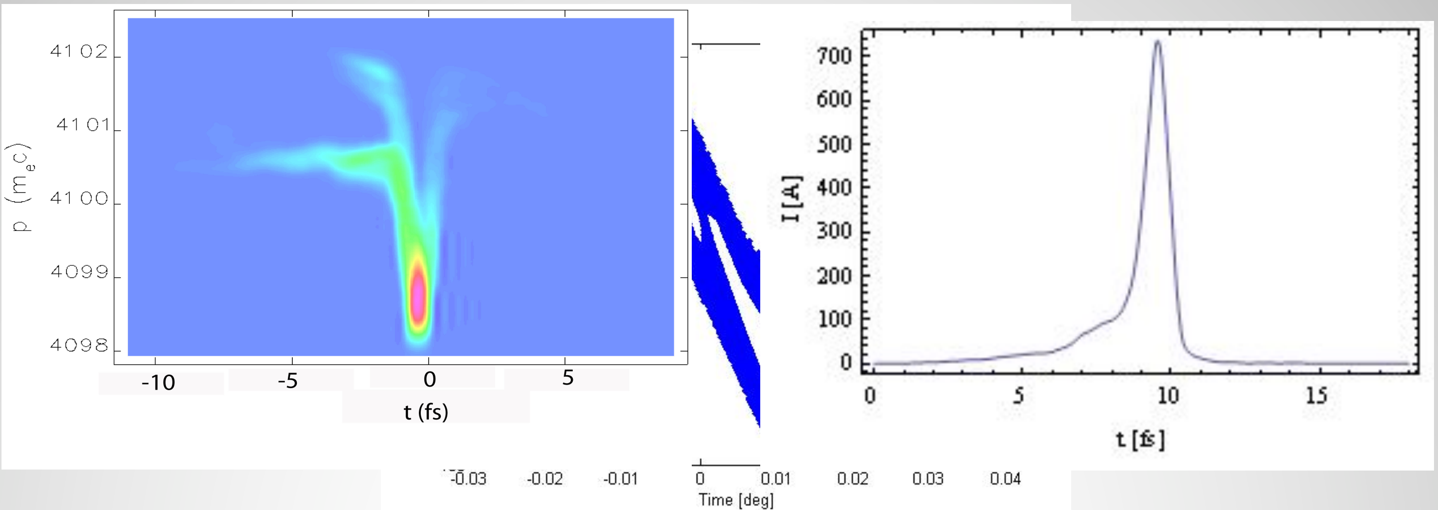
Beam physics: from plasma to plasma



- Beam at lower energy is single component relativistic *plasma*
- Preserve optimized dynamics: change *Q*, keeping plasma frequency (*n*, aspect ratio) same
- Dimensions scale as $\sigma_i \propto Q^{1/3}$
  - Shorter beam, easier to *compress*
  - Big emittance reduction, easy to *focus*
  - Result: ultra-high *brightness* beam

J.B. Rosenzweig and E. Colby, *Advanced Accelerator Concepts* p. 724 (AIP Conf. Proc. 335, 1995).

Ultra-short pulses at SPARX (LNF)



Final ongitudinal phase space

σ_z=4.7 μm after velocity bunching

Final current profile

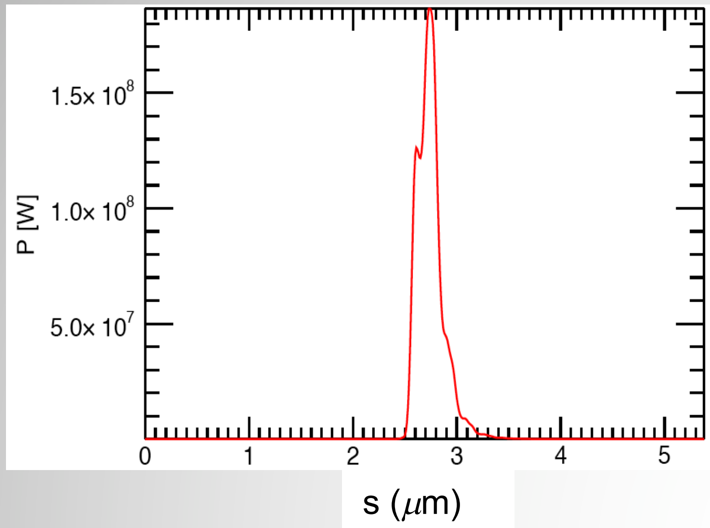
- Chicane bunching after velocity bunching
- Use ~1 *pC* beam for single spike
  - SS: cooperation length=bunch length
- Short, low emittance beam at final energy 2.1 GeV

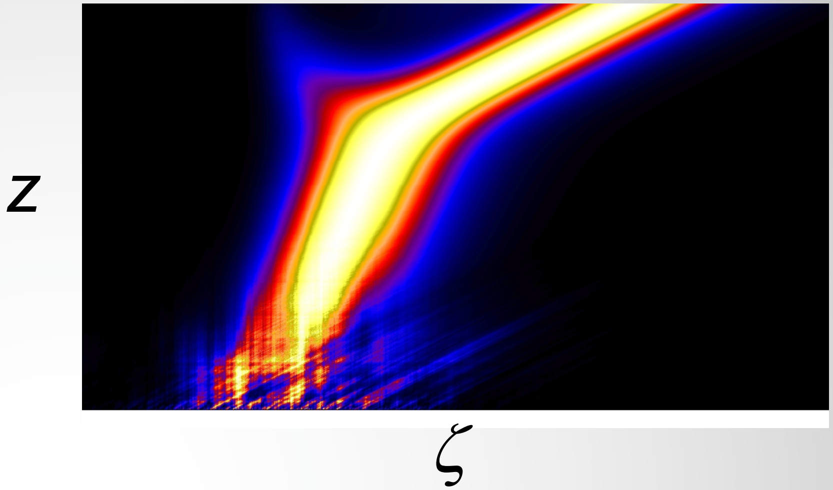
$$\varepsilon_{nx} \cong 7.5\times10^{-8}\ \text{m-rad} \qquad \sigma_t \cong 600\ \text{attoseconds(!)}$$

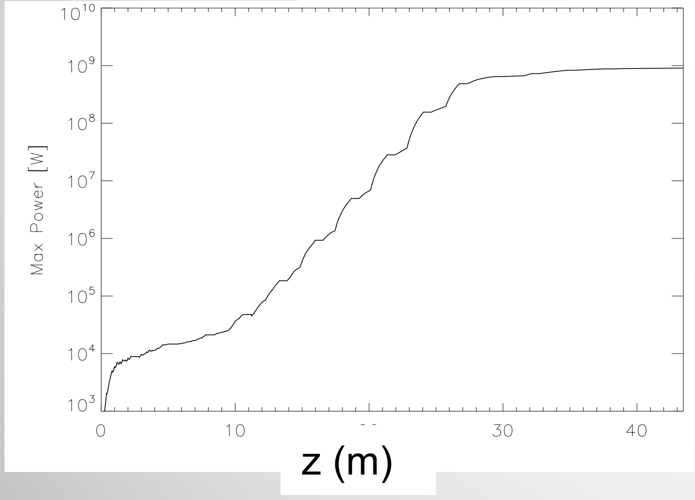
- Very high final brightness
  - 2 orders of magnitude!

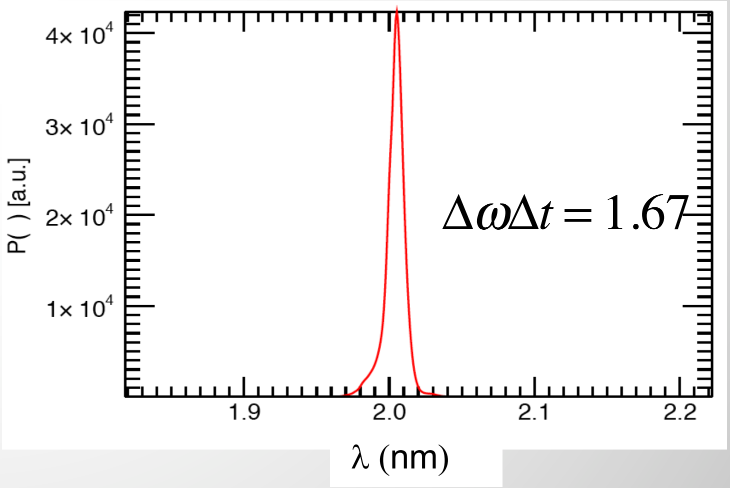
$$B = 2\times10^{17}\ \text{A/m}^2$$

Single Spike X-ray FEL





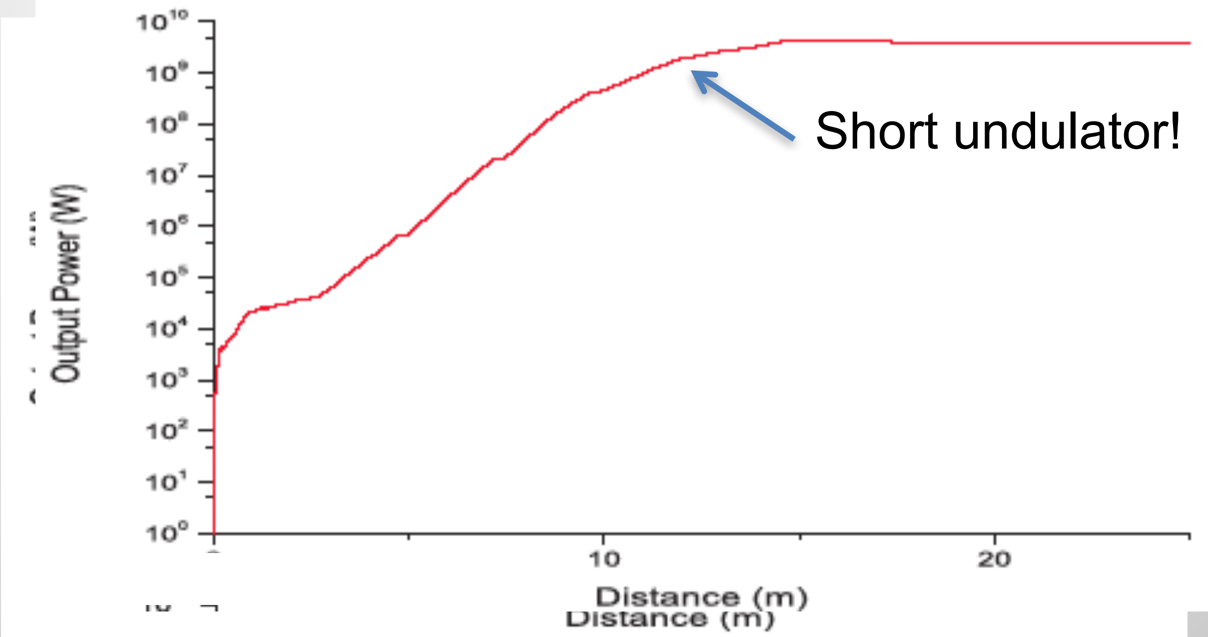




- Single spike, > 1 GW peak power
- 480 *attosecond* rms pulse at 2 nm
- 1st time in X-ray regime

Example: LCLS w/sub-fs pulse

- Use even shorter 0.25 pC beam, *150 as* pulse
  - Single spike w/standard LCLS undulator
- Obtain ultra-compact “LCLS” at 4.3 GeV
- Extend energy reach to 83 keV (0.15 Å)

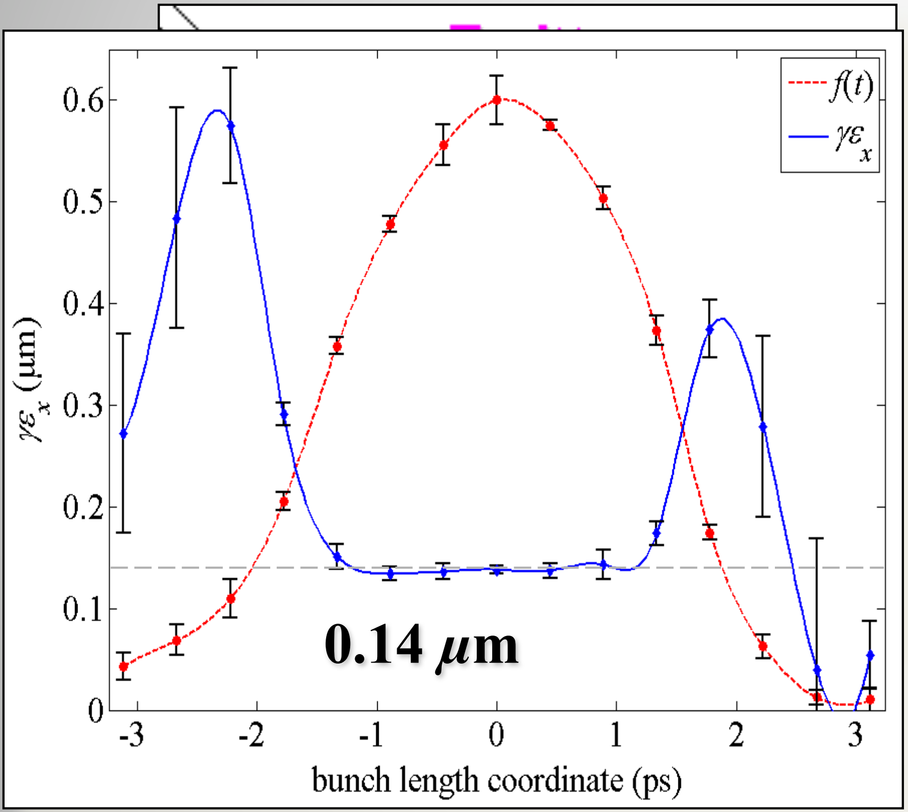


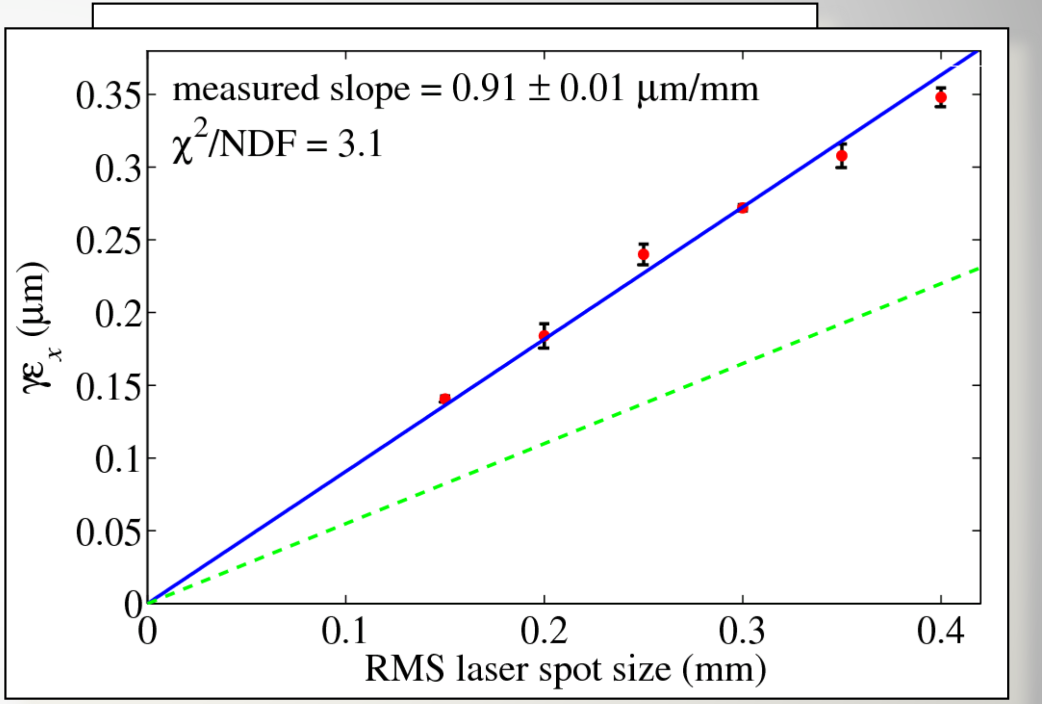
Gain evolution for 1.5 Å 4.3 GeV (0.25 pC)

Gain evolution at 13.6 GeV; 0.15 Å, 83 kV FEL

High interest in FEL community… low-Q explorations at LCLS

Low emittances at LCLS with *20 pC.* Diagnostic limited





OTR screen with
transverse
deflector ON

Emittance near calculated thermal emittance limit

20 pC, 135 MeV, 0.6-mm spot diameter, 400 *µ*m rms bunch length (5 A)

Measurements and Simulations for 20-pC Bunch at 14 GeV

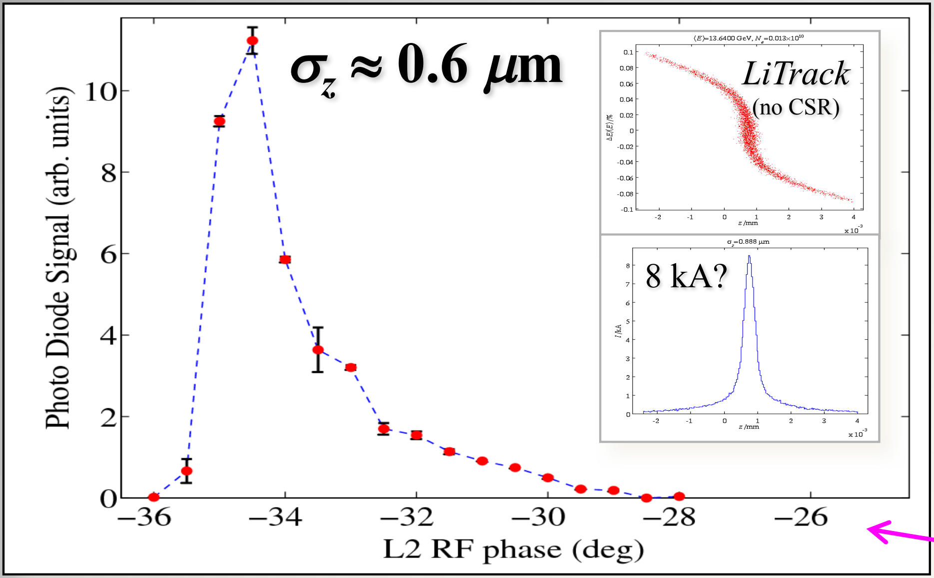
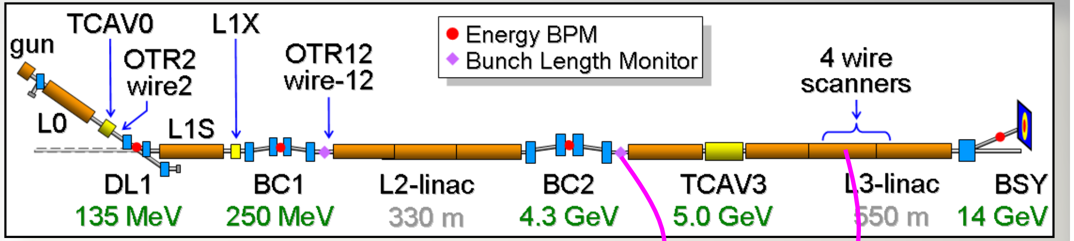
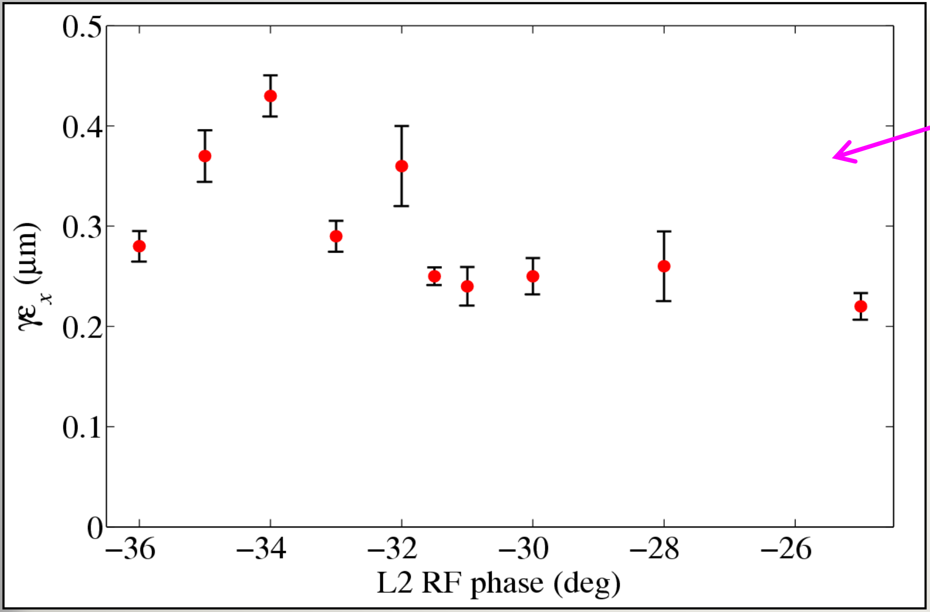
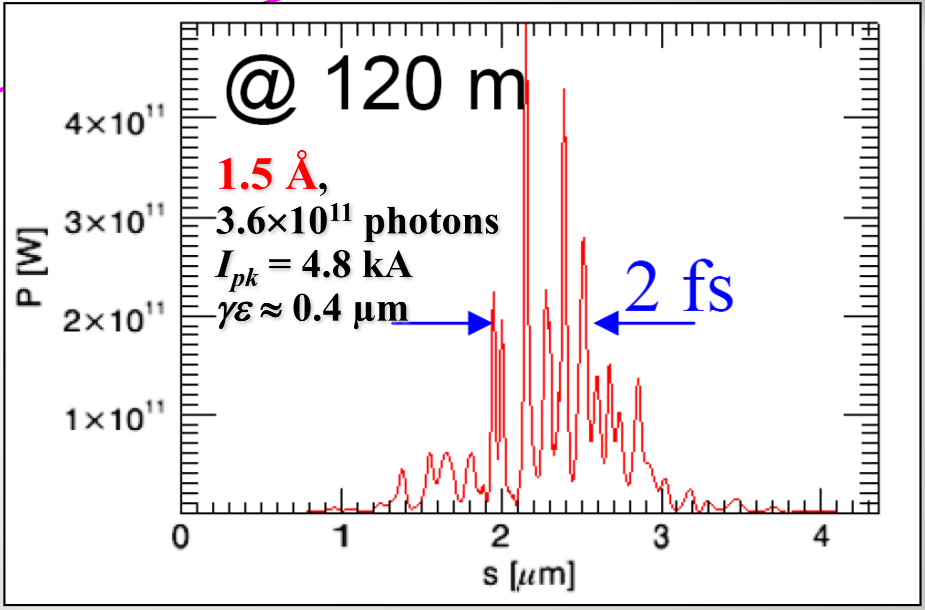


Photo-diode signal on OTR screen after BC2, best compression at L2-linac phase of -34.5 deg.





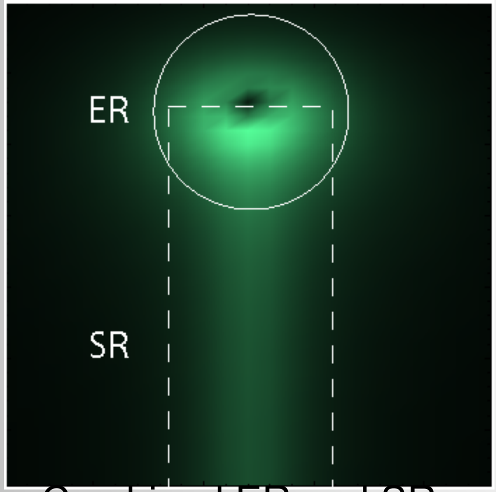
Horizontal projected emittance **measured** at 10 GeV



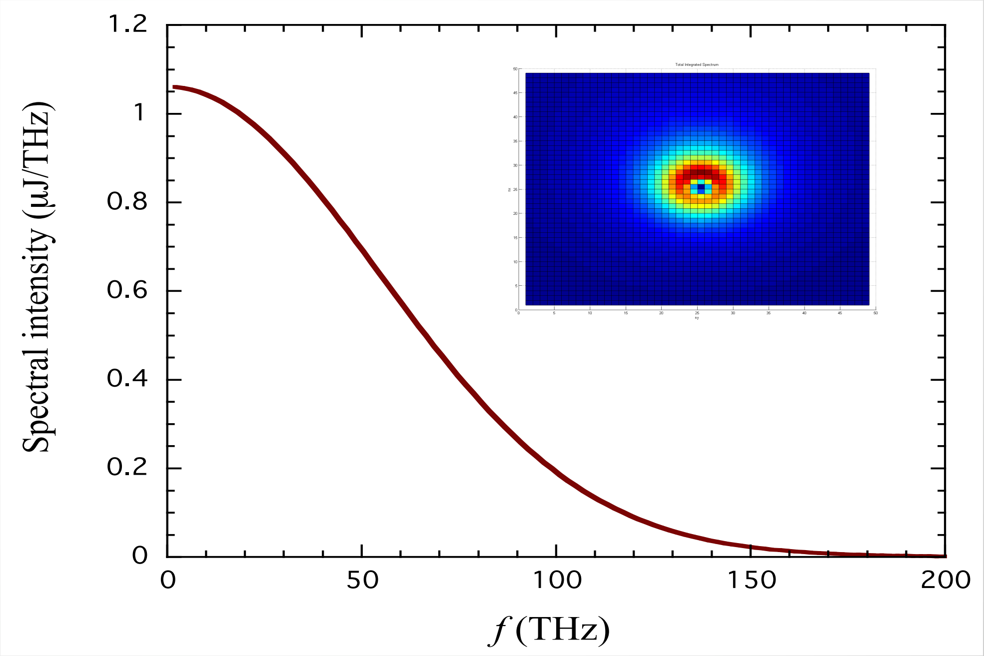
LCLS FEL **simulation** at 1.5 Å; not single spike.

2 fs beams at temporal measurement resolution limit

- Coherent transition radiation (destructive)
- Non-destructive: coherent edge radiation (CER)



Combined ER and SR

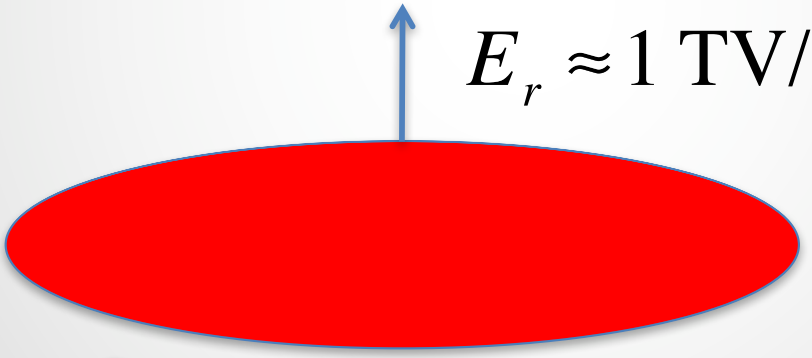


QUINDI simulation FACET II case

Advanced accelerator physics: focusing ultra-short beams

- 2 fs (600 nm) beam predicted to have I_p=8 kA
- Focus to σ_r<200 nm (low emittance enables…)
- Surface fields

$$eE_r \approx r_e m_e c^2 I_p / ec\sigma_r$$

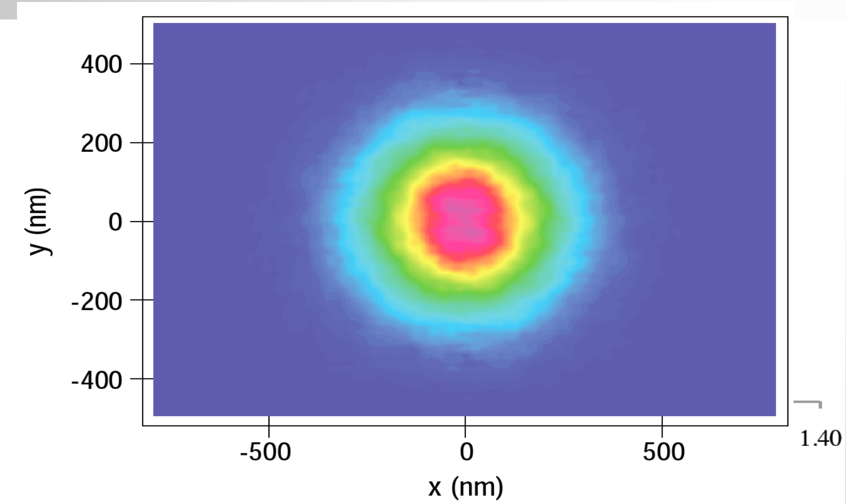


$$E_r \approx 1\ \text{TV/m!}$$

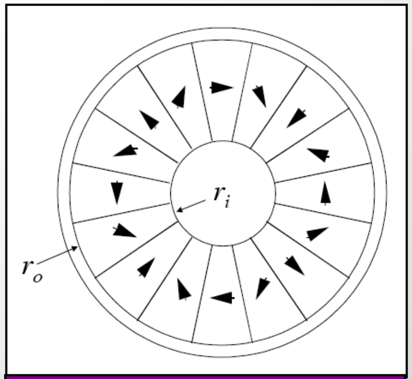
- TV/m (100 V/Å!) in fs unipolar (1/2-cycle) pulse
  - New tool for high field-matter interaction (AMO, nuclear)
  - FACET I limit ~100 GV/m – emittance too high!

How to focus?

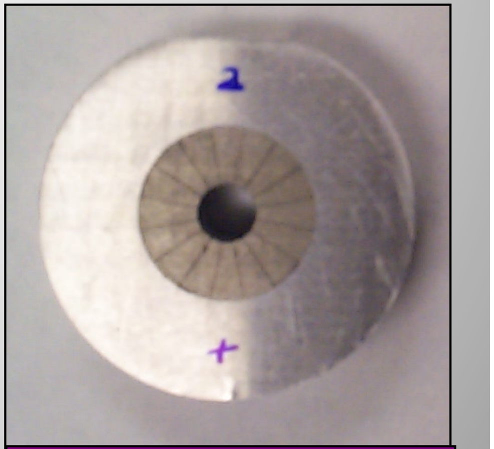
- Very short focal length final focus
- Use ultra-high field permanent magnet quads
  - mitigate chromatic aberrations
  - FF-DD-F triplet, adjust through quad placement
- Developed 570 T/m PMQ fields
  - Need slightly stronger, no problem (Pr gives >1kT/m)



Final beam sizes: ~130 nm



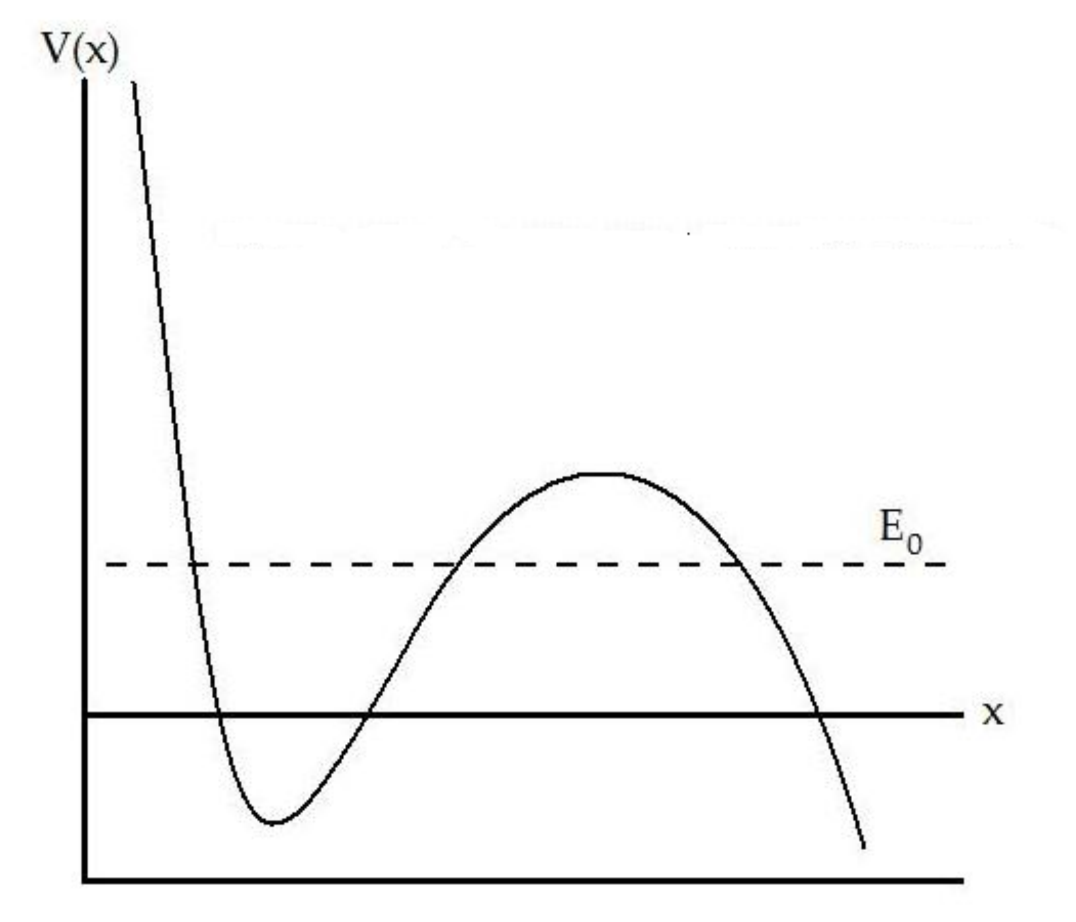
Small aperture PMQ B' =570 T/m



Halbach PMQ as built

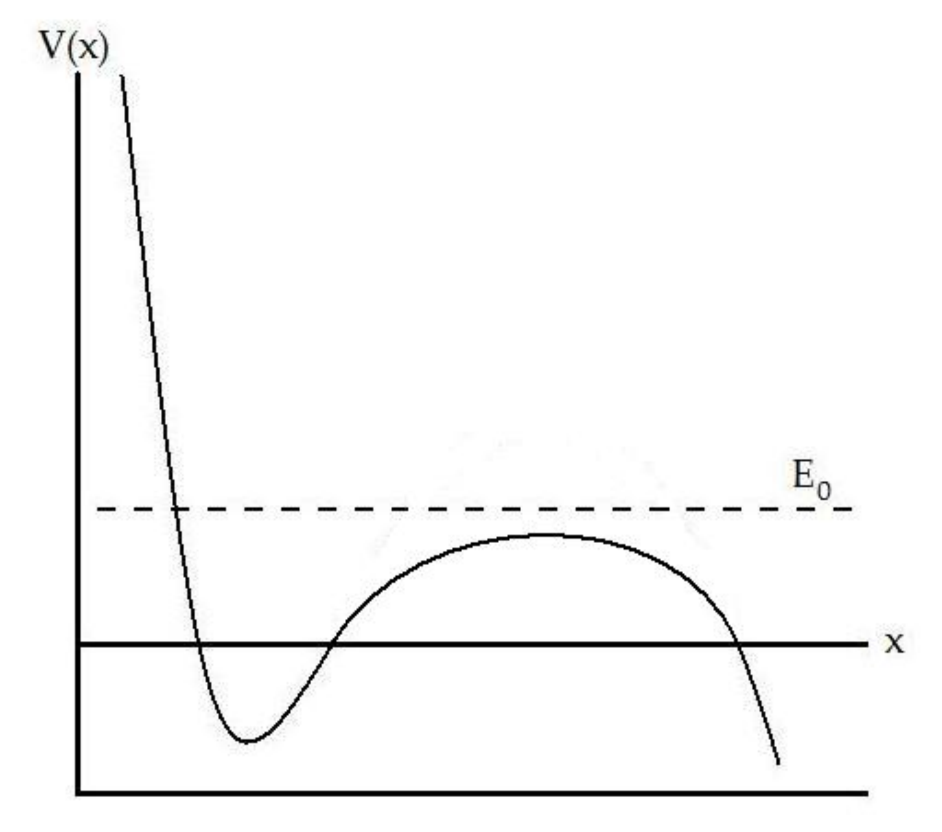
Collective Beam Field-induced Tunneling Ionization

- “Weaker” fields: tunneling
- Regime well understood
  - ADK perturbation theory
  - Developed for lasers
  - ADK-based simulation (OOPIC, Vsim)
  - Benchmarked to e-beam experiments (E167 and successors)



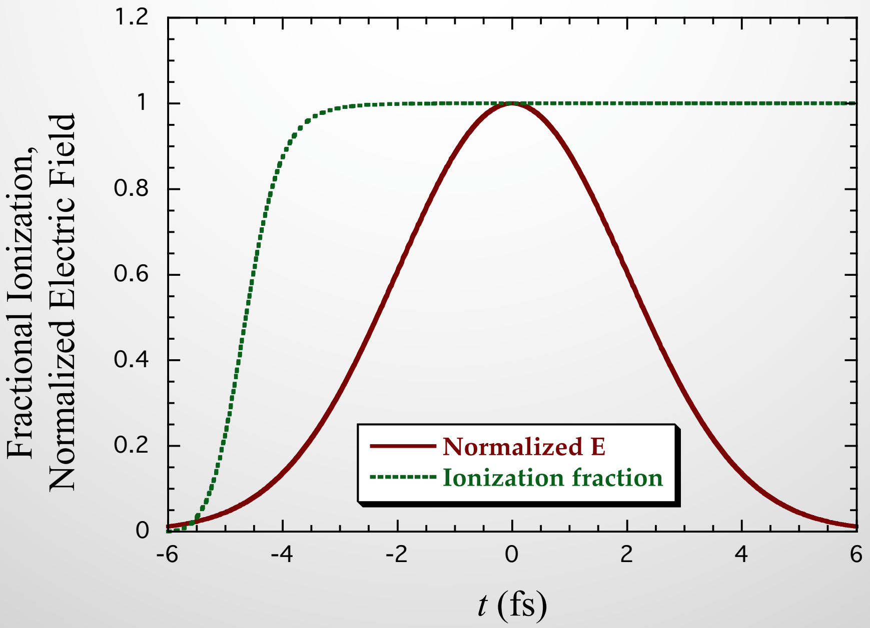
1 TV/m Reaches the Barrier Suppression Regime (BSI)

- BSI: e- classically escapes atom
  - Previously only reached experimental by lasers
  - Theory concentrates on lasers
- BSI not well understood
  - *Non-perturbative*
  - Empirical formulas
- Fundamental atomic physics tool
- Plasma wakefields…



BSI ionization occurs in 2 fs case

- Extension to unipolar field pulse
  - – approach of Bauer, et al. in laser context
- BSI important above 40 GV/m, but tunneling has already been accomplished…
- For total ionization trust OOPIC

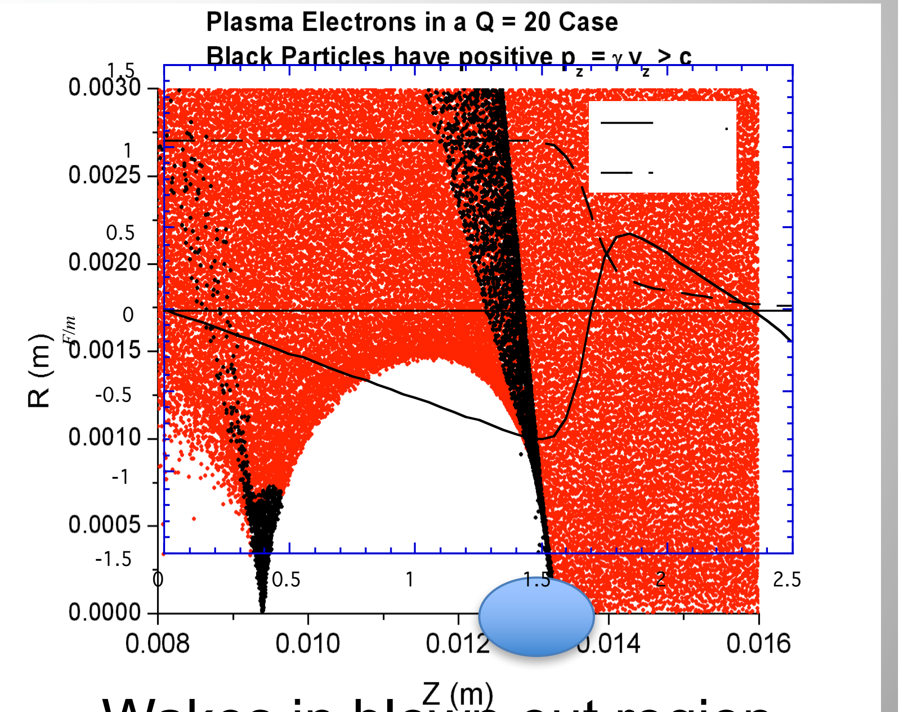


Fractional ionization due to BSI, 800 GV/m peak, 2 fs gaussian pulse

TV/m Plasma Wakefield Accelerator

- Ultra-high brightness, fs beams in plasma
- Use 20 pC LCLS beam in high *n* plasma
- In “blowout” regime: total rarefaction of plasma e^-s
  - Beam denser than plasma
  - Very nonlinear plasma dynamics
  - Pure ion column focusing for e-s
  - EM acceleration, independent of *r*
  - General measure of nonlinearity:

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_0} = 4\pi k_p r_e N_b \begin{cases} << 1, & \text{linear regime} \\ > 1, & \text{nonlinear "blowout"} \end{cases}$$



Wakes in blown out region

MAGIC simulation of blowout PWFA case

Single bunch excitation at FACET II

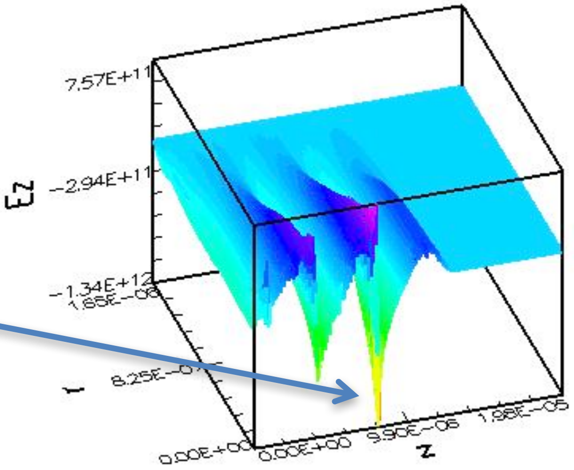
- Beam must be short and narrow compared to plasma skin depth $\sigma_r < k_p^{-1}$ $\sigma_z < k_p^{-1}$
- In this case $\tilde{Q} > 1$ implies $n_b > n_0$, blowout
- With 2 fs FACET II beam we choose $n_0 = 7 \times 10^{19}\ \text{cm}^{-3}$
- For 20 pC beam, we have $\tilde{Q} = 7$
- Linear “Cerenkov” scaling

$$eE_{z,dec} \cong e^2 N_b \int \frac{n(k)-1}{n(k)}\, dk \Rightarrow = e^2 N_b k_p^2$$

$$eE_{z,dec} = \frac{A e^2 N_b}{\sigma_z^2}$$

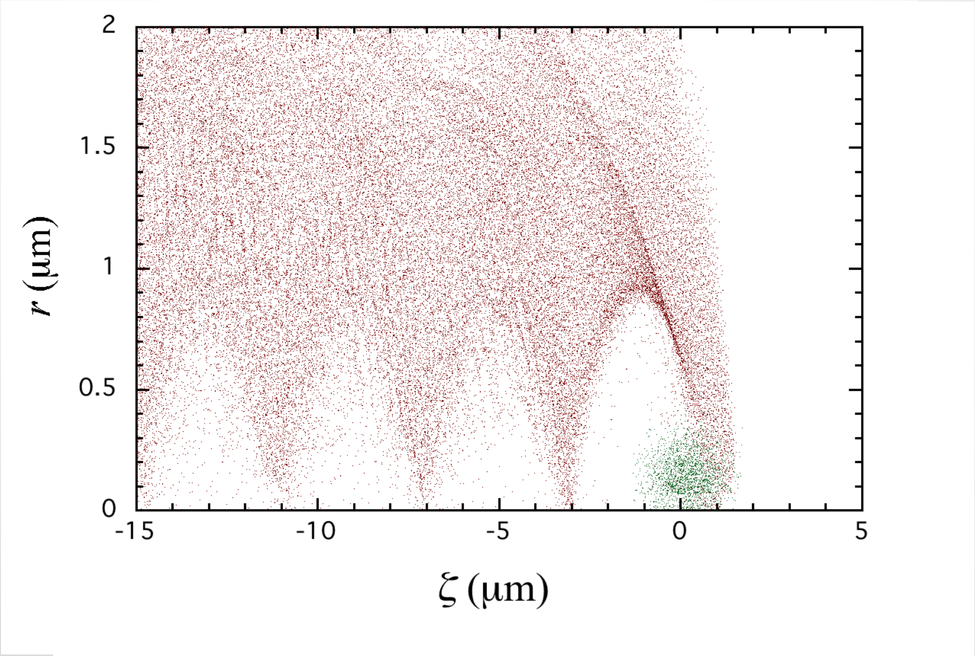
- *1 TV/m fields,* converted *E_r*)
- Collaboration initiated (authors)

OOPIC simulation of LCLS case



Beam-field induced ionization

- Focus beam to < 200 nm rms
- Radial E-field > TV/m
- Ionization studied in Li, H gas (ADK model, which applies in beam head…)



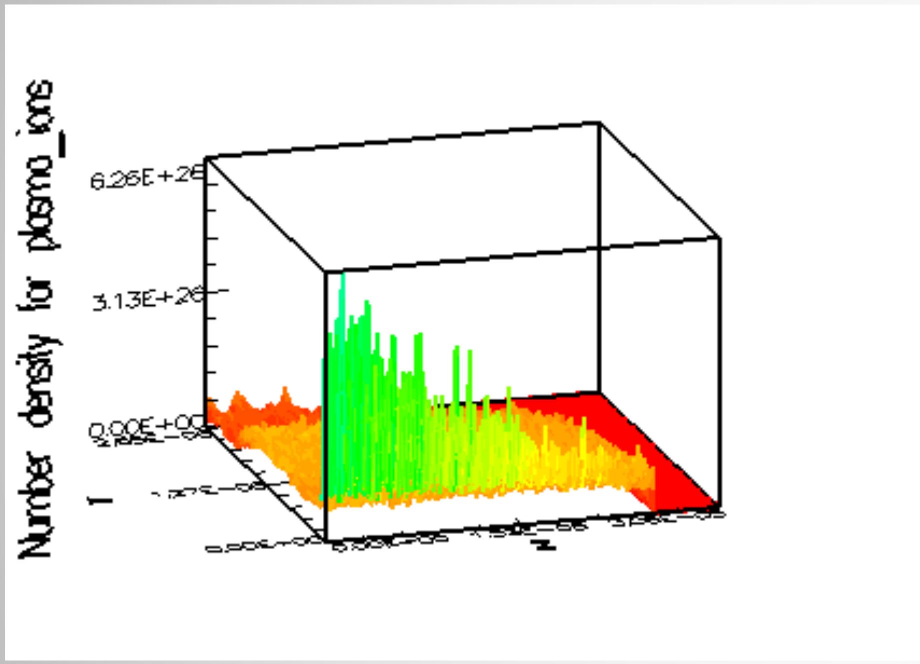
OOPIC study, 3.15 hydrogen ionized by beam

Hydrogen ionization complete inside beam

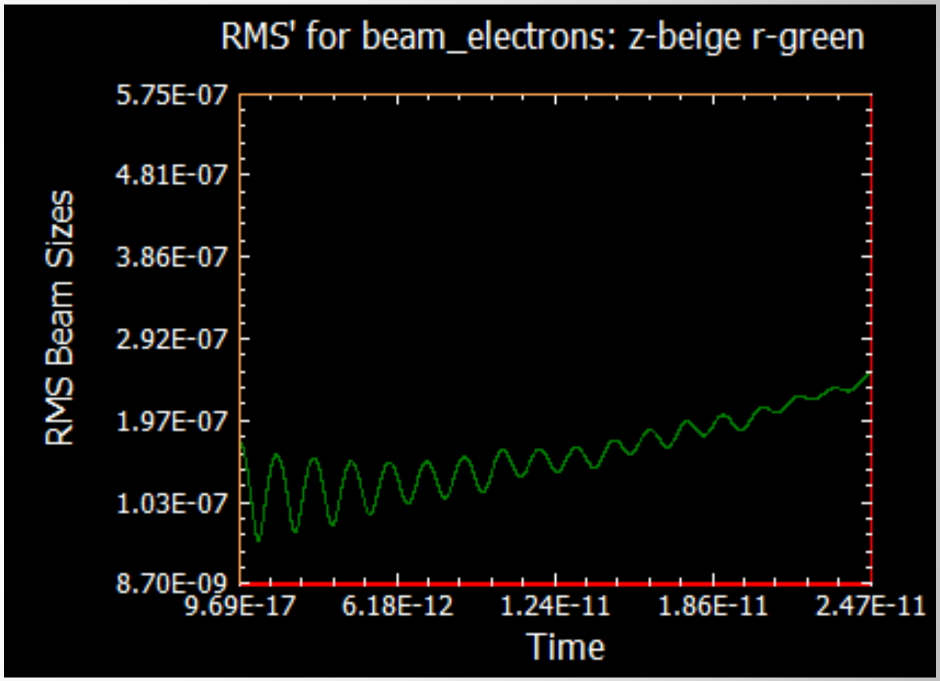
Complete ionization in Li

Well-focused, dense electron beam can lead to ion collapse

- Positive ions “focused” by ultra-dense e-beam fields



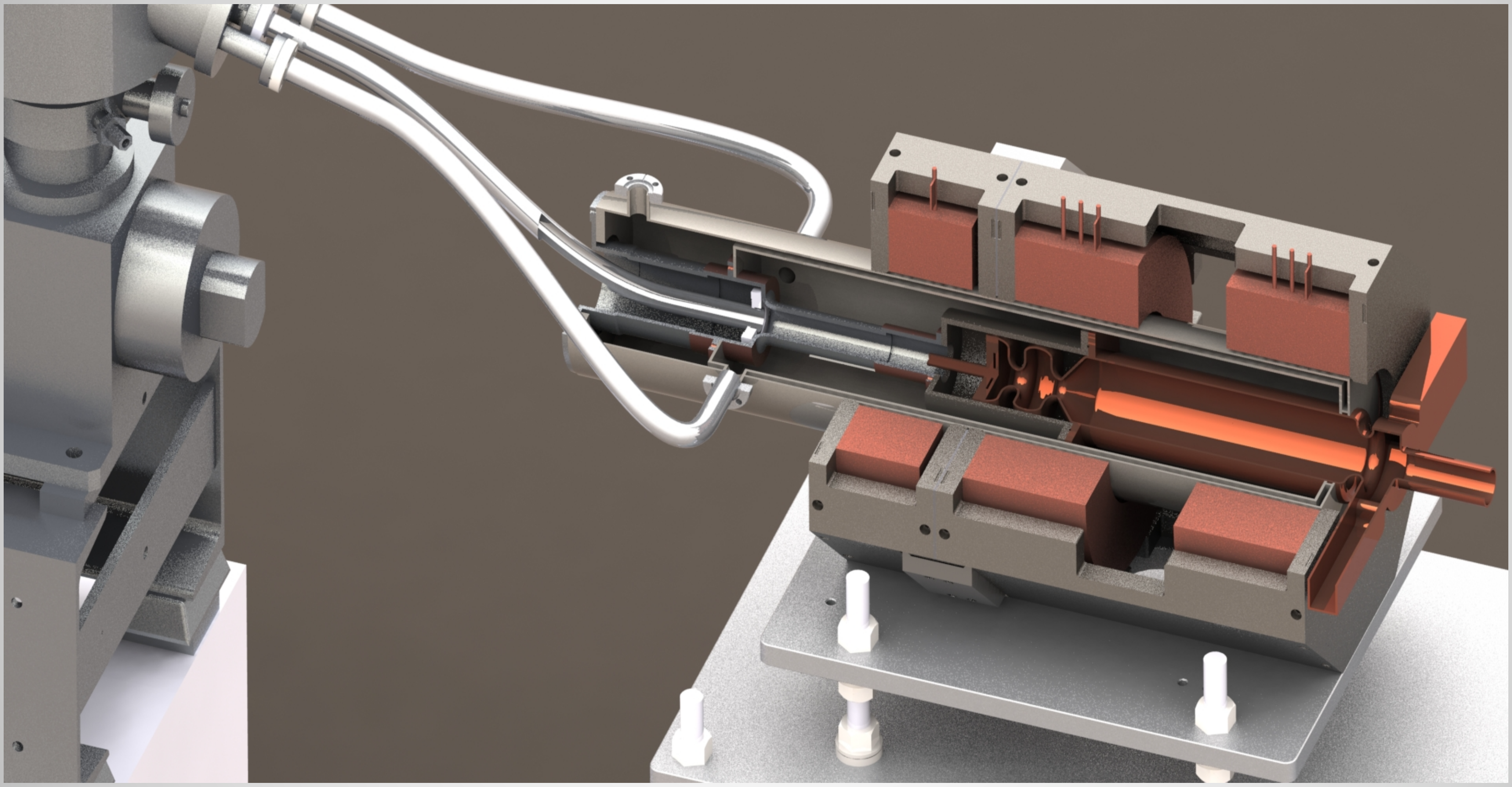
Non-uniform ion density enhancement



Beam mismatch and growth (ε-growth)

- Nonlinear fields, emittance growth. Bad for linear collider applications
- Detect 10-100 keV ions (hydrogen)

Increased brightness within reach



250 MV/m peak field S-band cryogenic gun with cryostat, focusing magnets

Brightness at photocathode

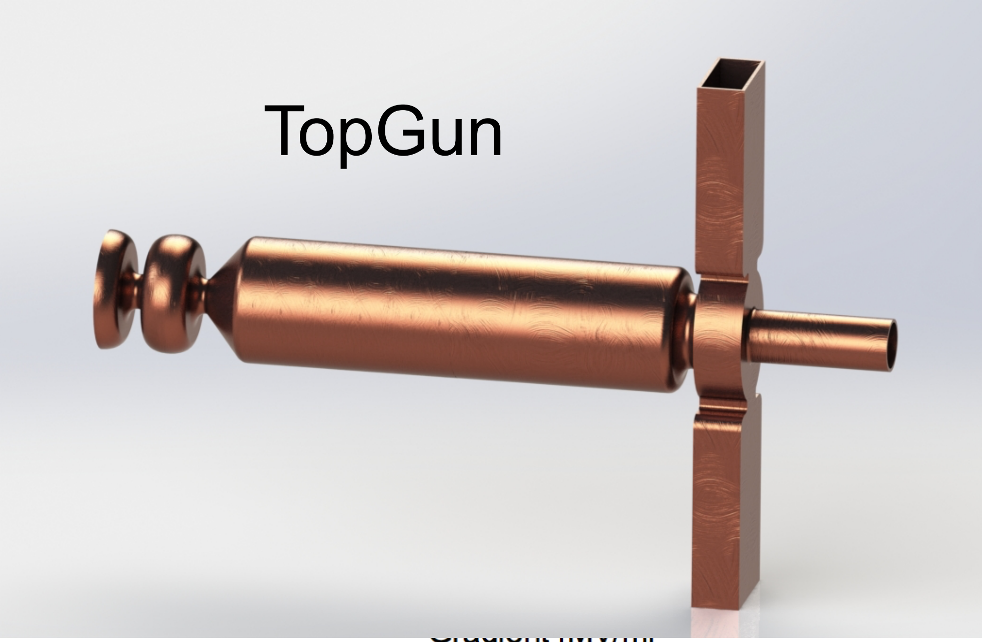
- *Brightness* at cathode: $B_e = \frac{2I}{\varepsilon_n^2} = \frac{2J_{\max} m_e c^2}{k_B T_c}$
- In 1D limit, peak current from a pulsed photocathode is

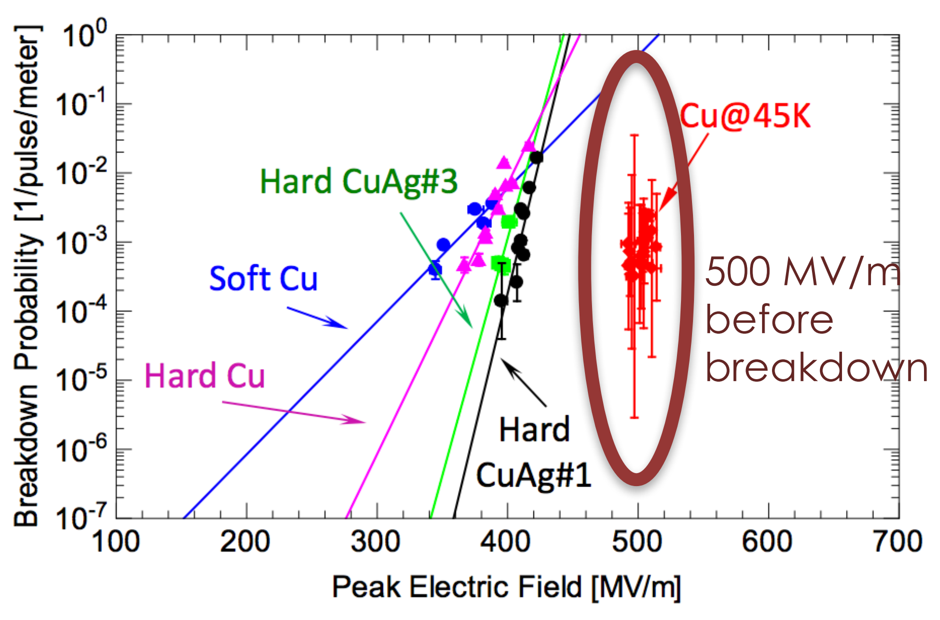
$$J_{z,b} \approx \frac{ec\varepsilon_0}{m_e c^2}\left(E_0 \sin\varphi_0\right)^2$$

- Brightness is $\boxed{B_{e,b} \approx \frac{2ec\varepsilon_0}{k_B T_c}\left(E_0 \sin\varphi_0\right)^2}$
- Lower emission temperature and/or…
- **Lesson: increase launch field**

Dramatically higher gradients in higher yield strength materials

- SLAC X-band studies on hard Cu, CuAg alloy show great improvement
- ***Cryogenic structures*** give yet higher gradients, *and* lower dissipation



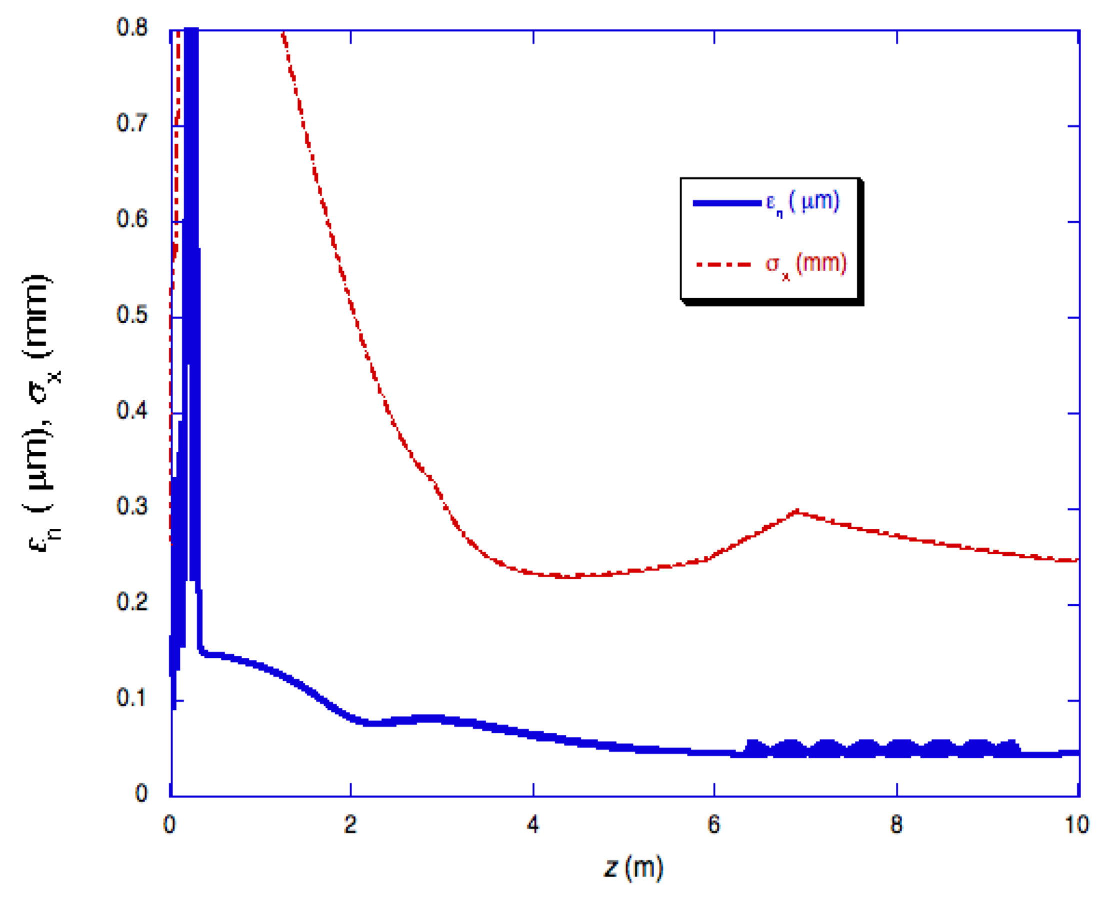


Game changing technique for high launch fields

Practical limit (dark current) ~300 MV/m presently

GPT simulation of 200 pC case

- Use long cigar-like beam (10 ps)
- Emittance ε_n=45 nm-rad
  - Ten times smaller than previous example



Current ***I***=20 A
Brightness a record for this charge

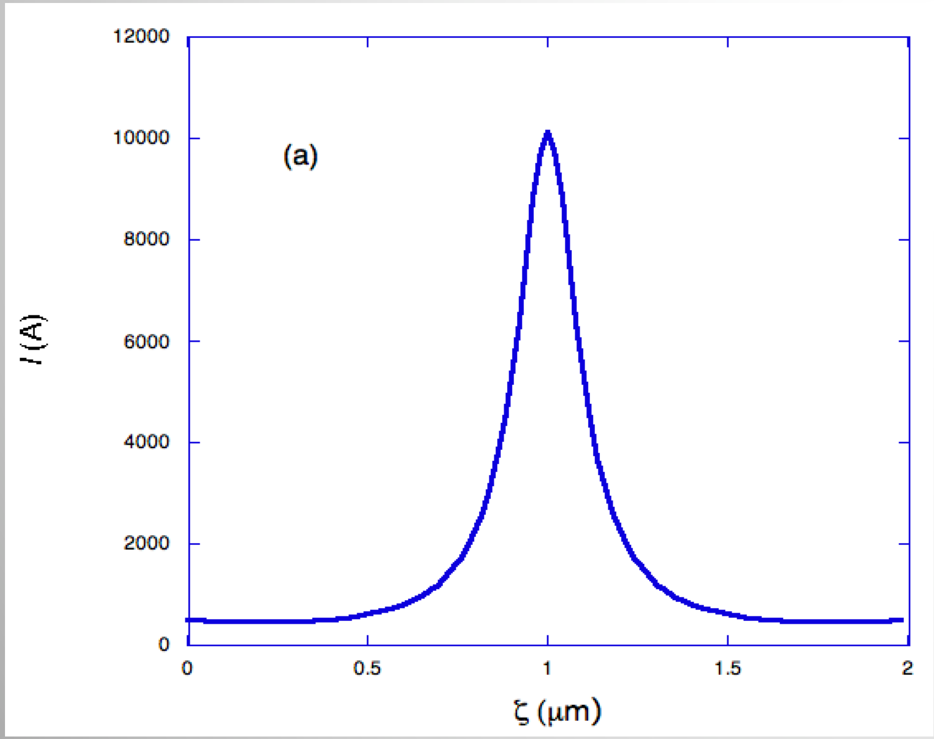
$$\boxed{B_e = 2\times10^{16}\ \text{A/m}^2}$$

This is **six times** what is available at a *reoptimized* LCLS

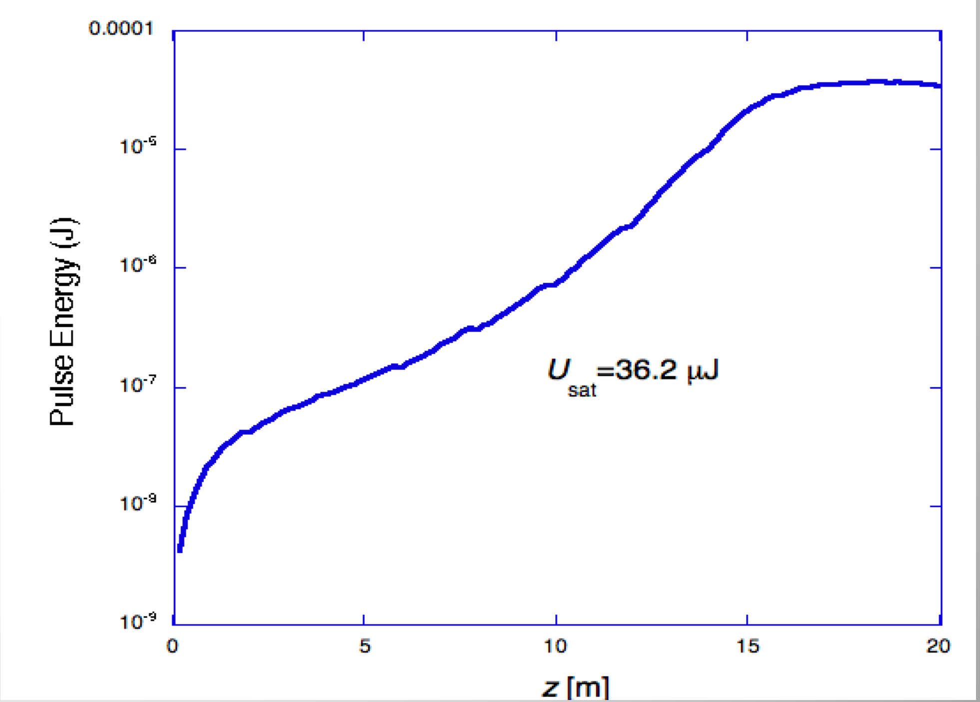
Compression is hard. Use ESASE microbunching

ESASE results at 100 pC

- 100 pC (10 ps), **36 nm** emittance
- Short period *cryo-undulator,* λ=9 mm, K=1.8
- Operation at 14 GeV gives **80 keV X-ray**
- Saturation in <20 m, with 70 GW peak



Current profile (10 kA)



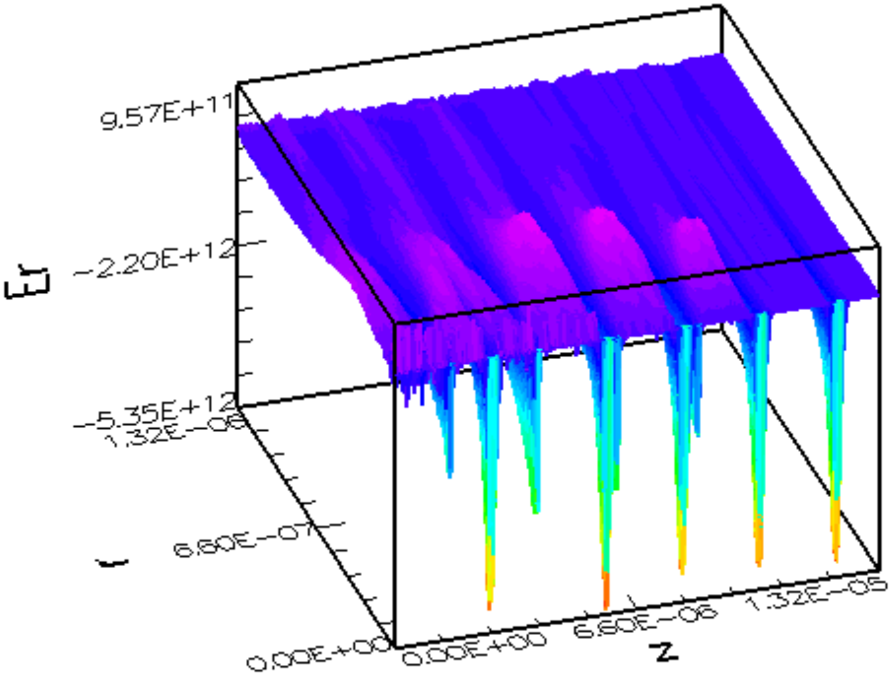
Energy evolution

Using 10 kA peak microbunched beam in PWFA

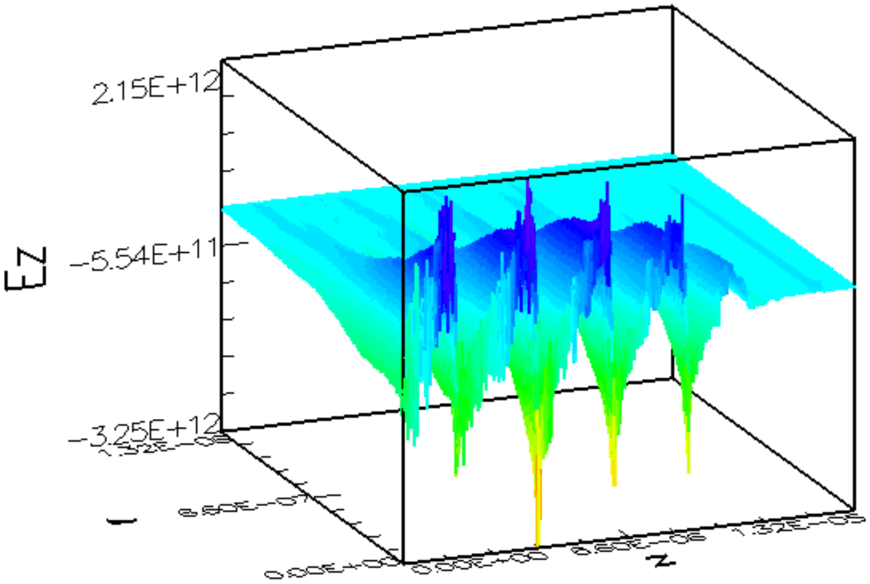
- Utilize quasi-nonlinear (QNL) regime periodic excitation (υbunching period = plasma period)

$$n_0 = 2.5 \times 10^{20} \text{ cm}^{-3}$$

- Highly focused beam (22 nm), peak E_r>5 TV/m



4 drive pulses + witness

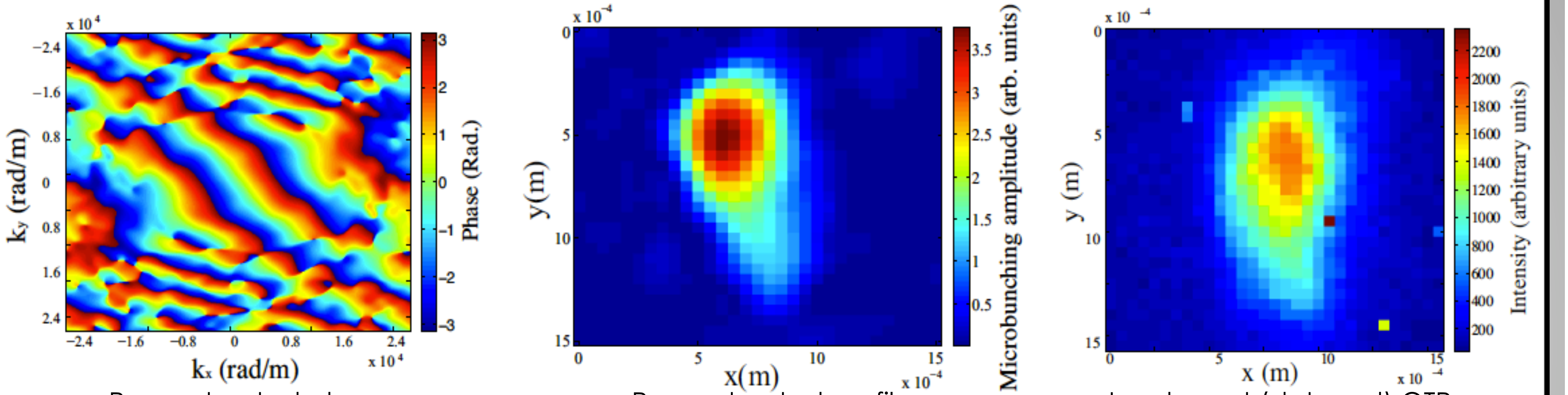


Resonant excitation to >3 TV/m

Experimental implementation

- Beam focusing
  - Few-100 nm beam demands mini-beta PMQs
- Plasma section
  - ~3-30 atm gas jet, with BSI. Start with tenuous gas
  - Length ~0.5 mm gives ~GeV ΔE, “perturbative”
- Beam diagnostics in entirely new regime
  - Longitudinal: coherent edge/transition radiation
  - Transverse:
    - Ionization, appearance intensity
    - coherence

Sub- μm beam transverse diagnosis



Reconstructed phase

Reconstructed profile

Incoherent (detuned) OTR

Coherent transition radiation imaging reconstruction expt., A. Marinelli et al., *PRL* 110, 094802 (2013)

- Measure sub-μm beam sizes with *coherent imaging* (borrowed from XFEL). Coherent information down to 100 nm?

Conclusions

- Attosecond e-beams can be reached at low Q
- Greatly enhanced beam brightness
  - Single spike, compact FELs
  - New high field sources, enhance wavelength range
- Frontier regime for beams; coherent optical radiation, ionization, new diagnostics
- Enables new frontiers:
  - Extreme plasma wakefield accelerators
    - TeV/m at 1 atm
    - Resonantly driven optical/IR wavelengths (beam is easier, better!)
    - Ultra-high field atomic-physics – TV/m unipolar field