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

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FACET-II Science Workshop
October 17, 2016

Outline

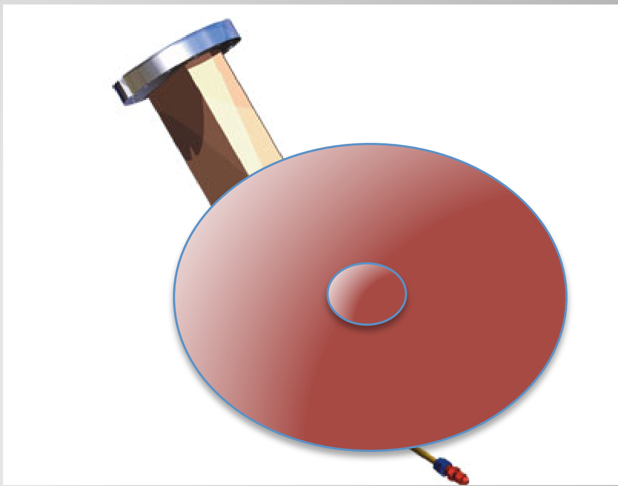
- Genesis of the idea: proposal for ultra-short beams in SASE FEL
  - Ultra-high brightness electron beams at low *Q*
  - Breaching attosecond, short wavelength frontier
- Coherent radiation from ultra-short beams
- Scaling the PWFA to short wavelength
- TV/m PWFA experiment at the LCLS

Ultra-short XFEL pulses: motivation

- Investigations at atomic *electron* spatio-temporal scales
  - Angstroms-nanometers (~Bohr radius)
  - **Femtoseconds** (e^- motion, Bohr period; femto-chemistry, etc.)
- Many methods proposed for the fs frontier
  - Based on optical slicing, etc.
  - Drawbacks: noise pedestal, low flux,…
- Use "clean" ultra-short, low charge electron beam
  - Myriad of advantages in FEL *and* beam physics
    - Mitigate collective effects dramatically
  - Robust in application: XFEL, coherent optical/IR source
  - *Spin-off* to ultra-high field PWFA…

Beam physics: from plasma to plasma

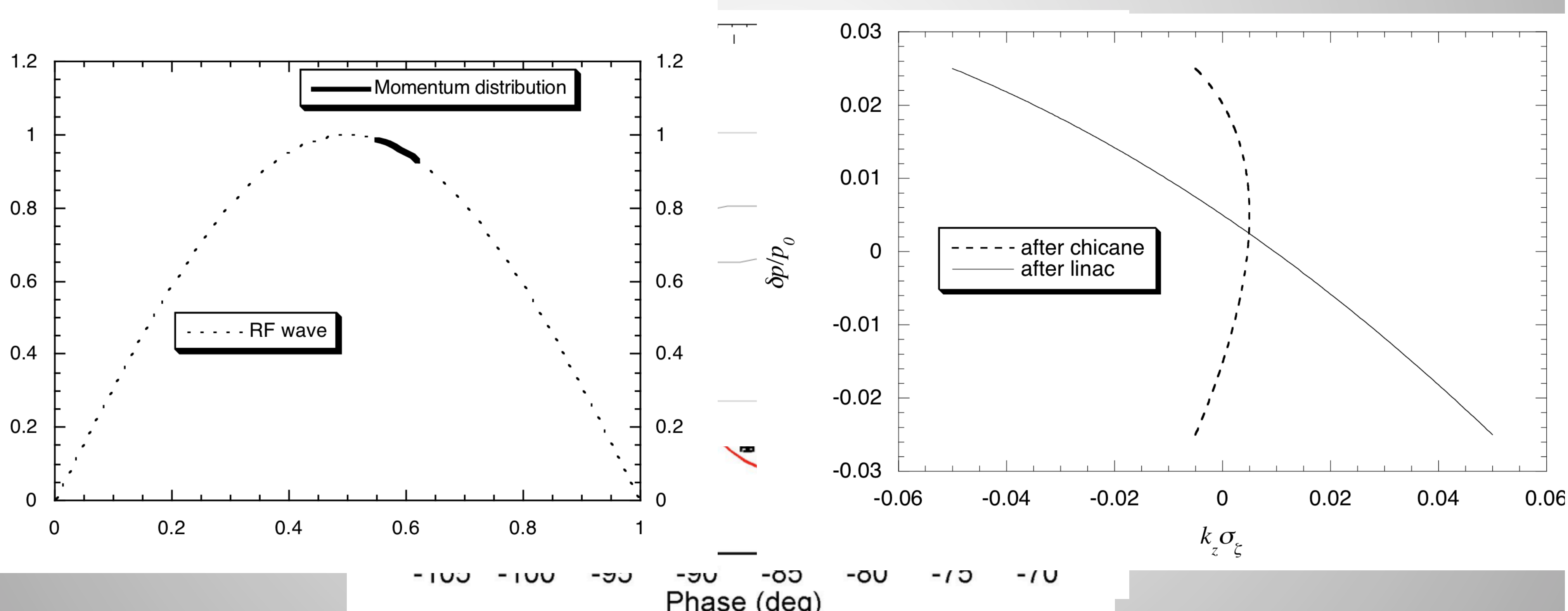
- Beam at lower energy is single component relativistic *plasma*
- Preserve optimized dynamics: change *Q*, keeping plasma frequency (*n*, aspect ratio) same
- Dimensions scale $\sigma_i \propto Q^{1/3}$
  - Shorter beam, easier to *compress*
  - Big emittance reduction, easy to *focus*
  - Result: ultra-high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



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

Bunching for high currrent

- **Magnetic chicanes recently enhanced by velocity bunching**
  - Avoids coherent beam degrading effects in bends
- Collective effects mitigated at low charge

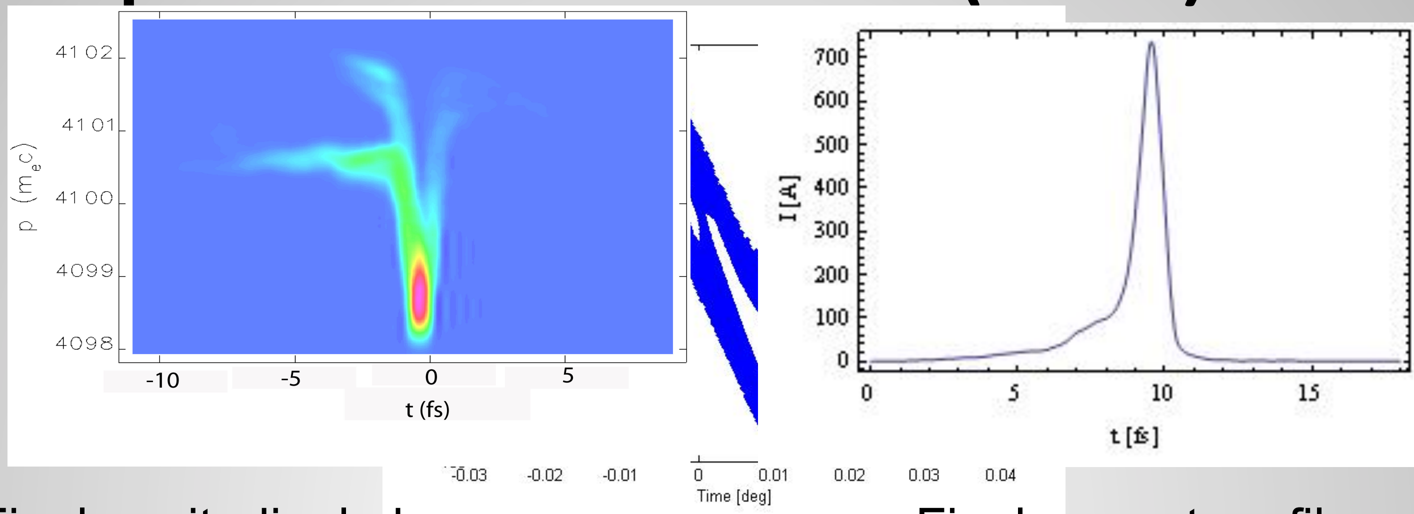


Longitudinal phase space schematic for velocity bunching

Recent velocity bunching results from SPARC (INFN-LNF, Frascati)

M. Ferrario et al., Phys. Rev. Lett. 104, 054801 (2010)

Original proposal: ultra-short pulses at SPARX (LNF)



Final ongitudinal phase space σ_z=4.7 μm after velocity bunching Final current profile

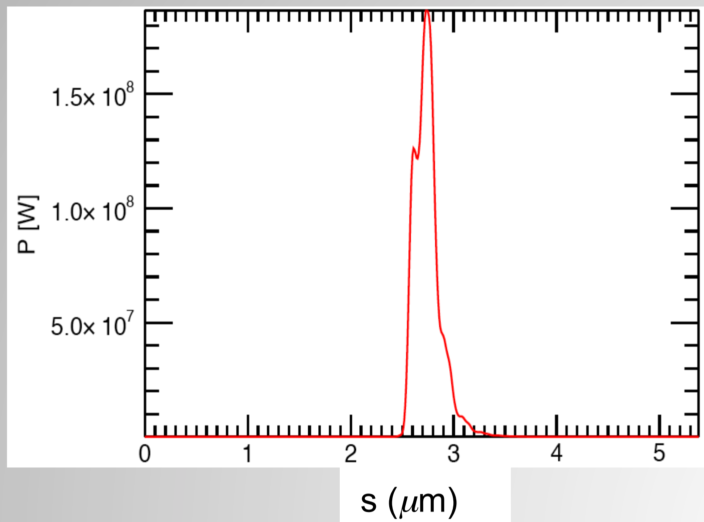
- Chicane bunching after velocity bunching
- Use ~1 *pC* beam for single spike
  - SS: cooperation length=bunch length
- Short, low emittance beam at final energy 2.1 GeV

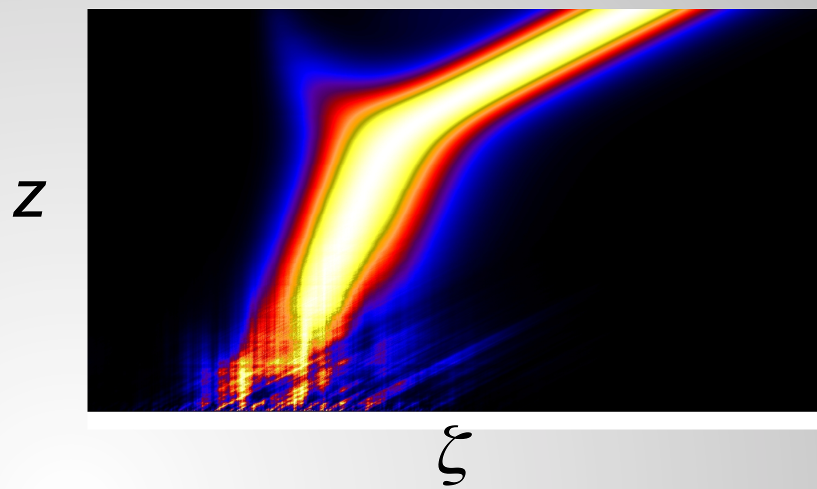
$$\varepsilon_{nx} \cong 7.5\times 10^{-8}\ \text{m-rad} \quad \sigma_t \cong 600\ \text{attoseconds}$$

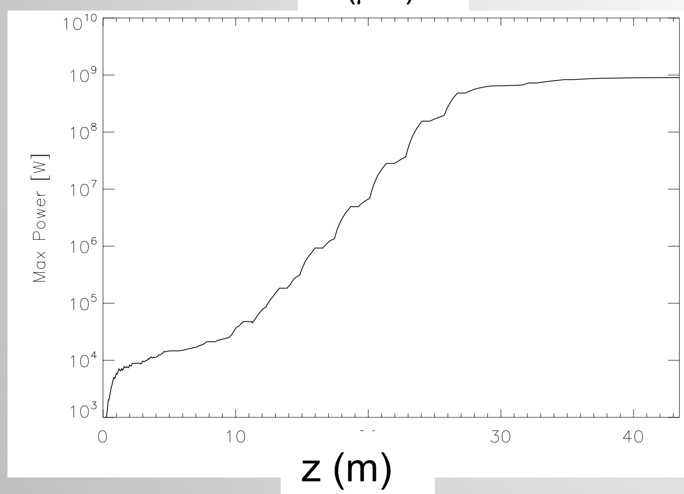
- Very high final brightness
  - 2 orders of magnitude!

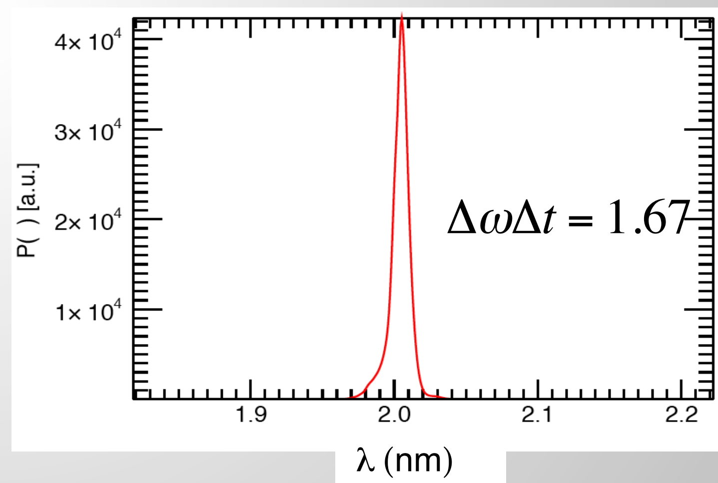
$$B = 2\times 10^{17}\ \text{A/m}^2$$

Single Spike X-ray FEL





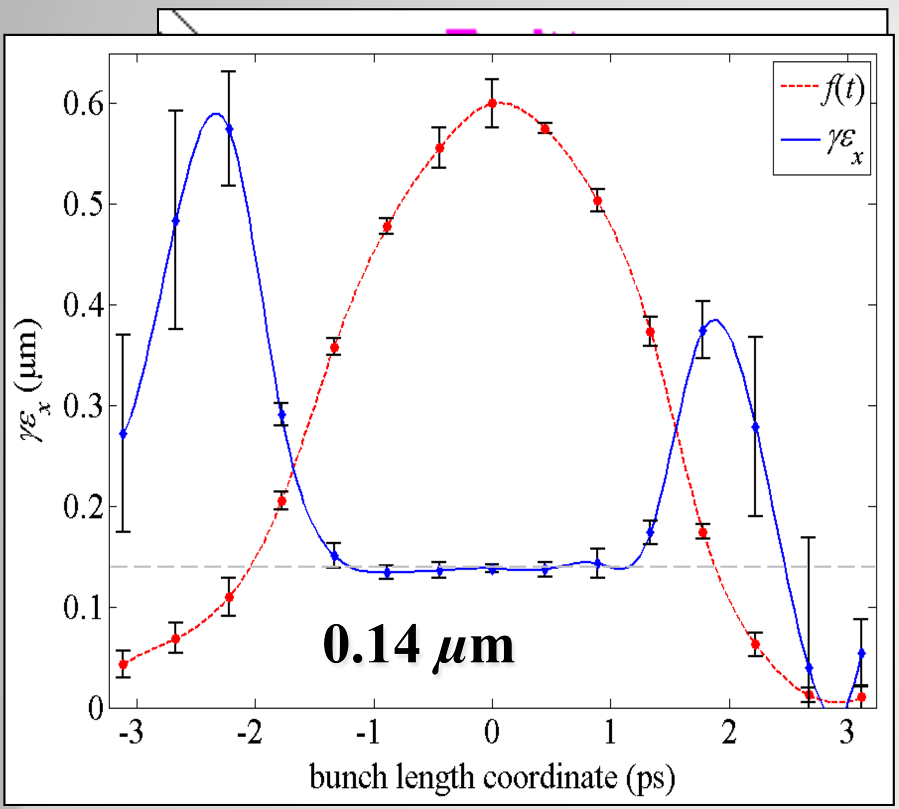


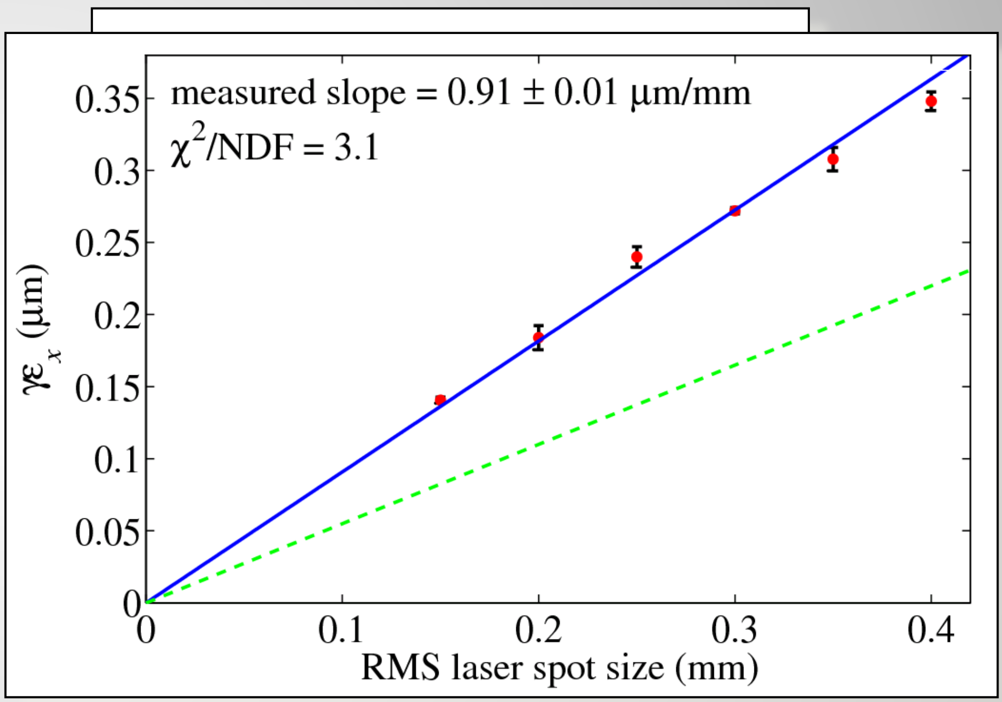


- Single spike, > 1 GW peak power
- 480 *attosecond* rms pulse at 2 nm
- 1st time in X-ray regime

Much traction in FEL community…
low-Q operations exploreed 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

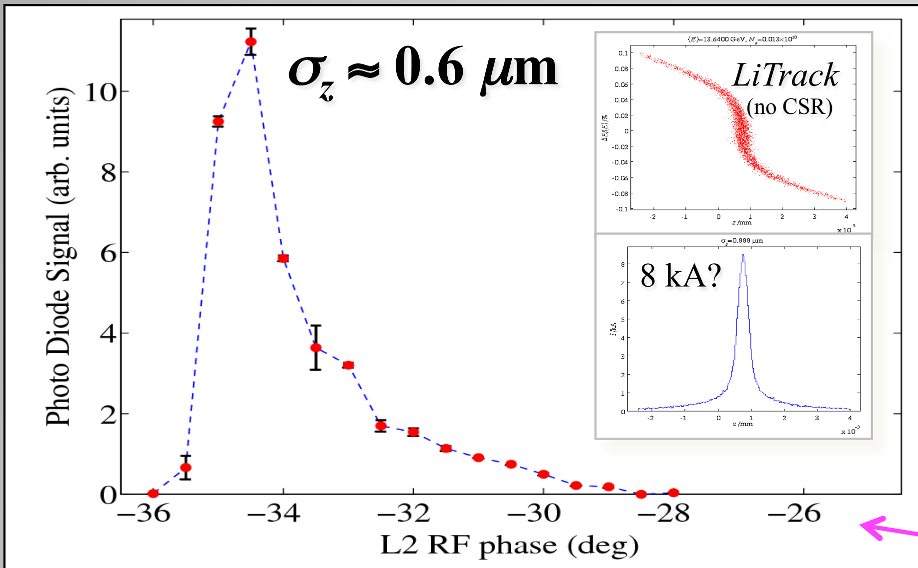
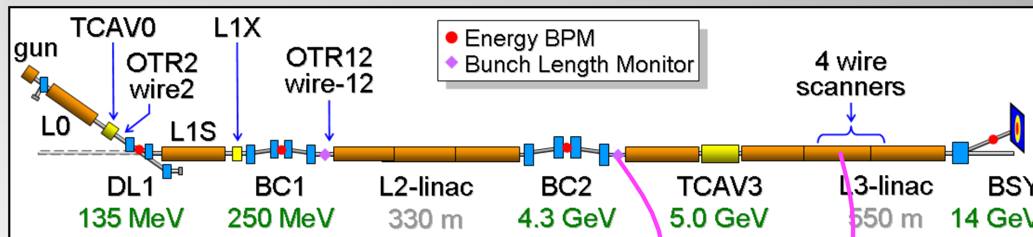
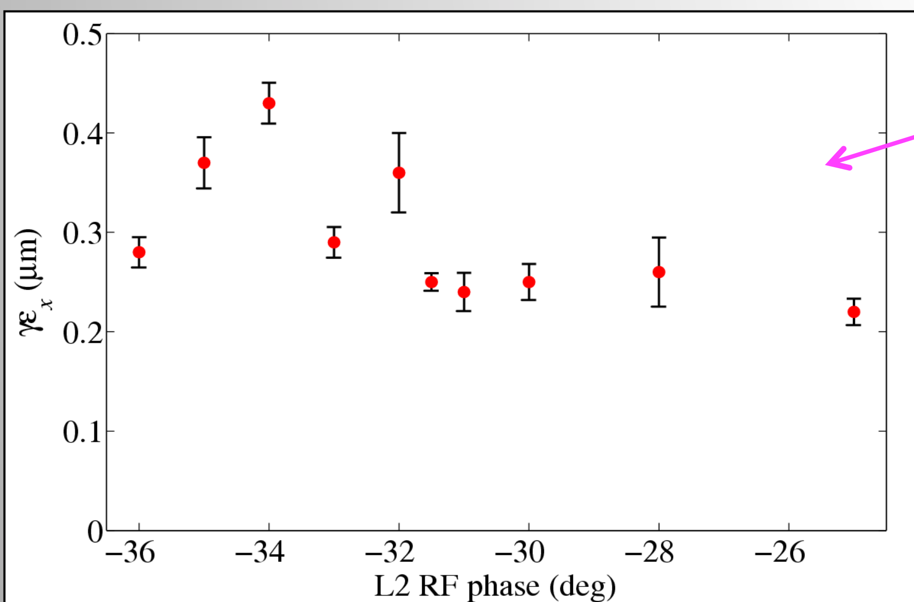
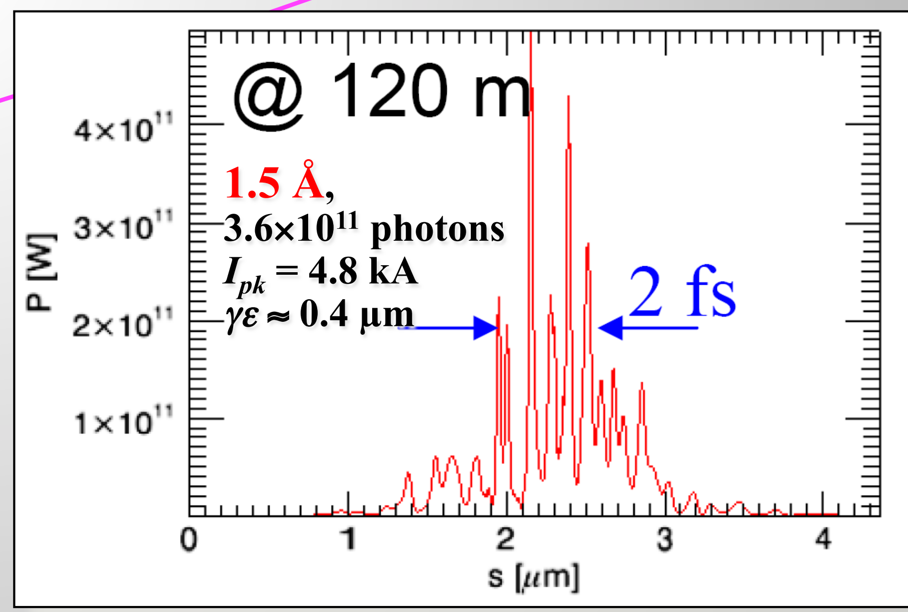


Photo-diode signal on OTR screen after BC2, best compression at L2-linac phase of -34.5 deg.





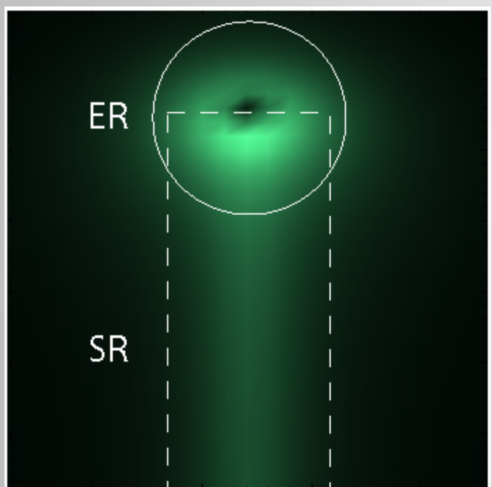
Horizontal projected emittance **measured** at 10 GeV



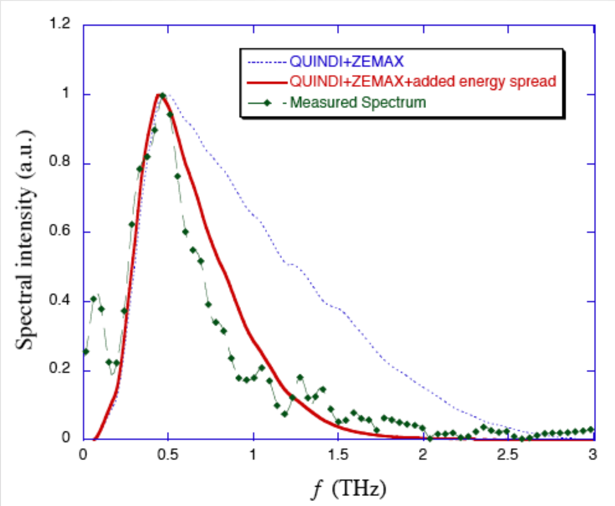
LCLS FEL **simulation** at 1.5 Å; not single spike.

2 fs beams: at measurement resolution limit

- Destructive: coherent transition radiation, RF sweeper
- Non-destructive: coherent edge radiation (CER)



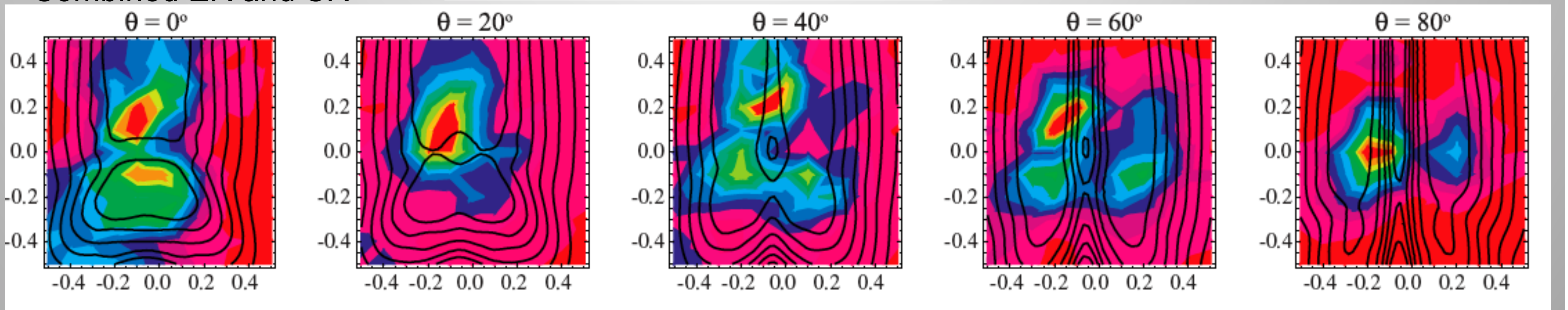
Combined ER and SR



Total emitted CER spectrum (BNL ATF, UCLA compressor), measured compared to simulation.

Coherent THz pulses observed

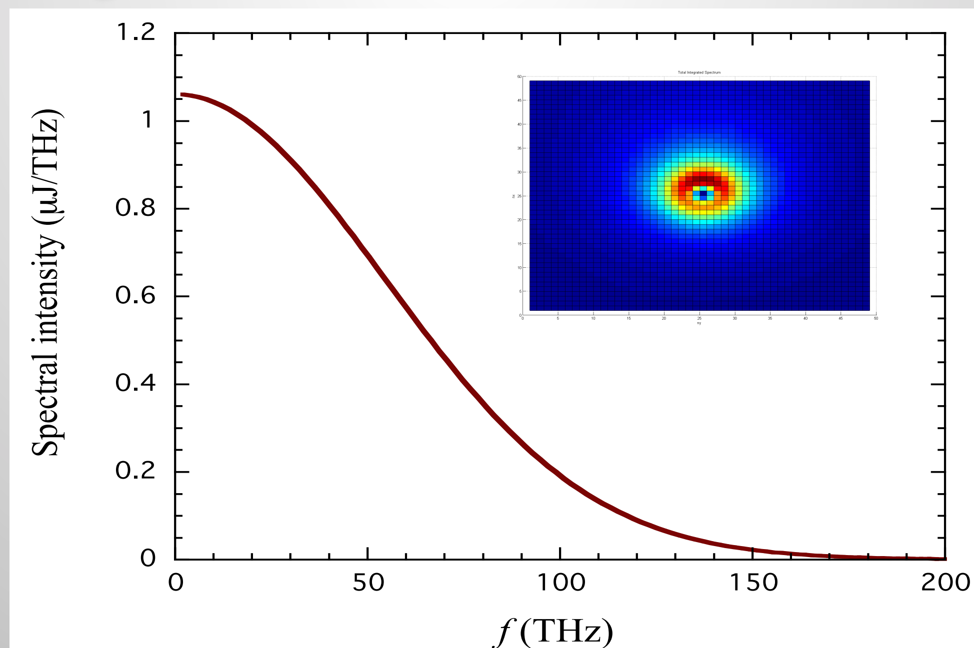
G. Andonian,, Phys. Rev. ST Accel. Beams 12, 030701 (2009)



Angular distribution of far-field radiation, by polarization: measured in color, simulation in contours

Coherent optical-IR sub-cycle pulse

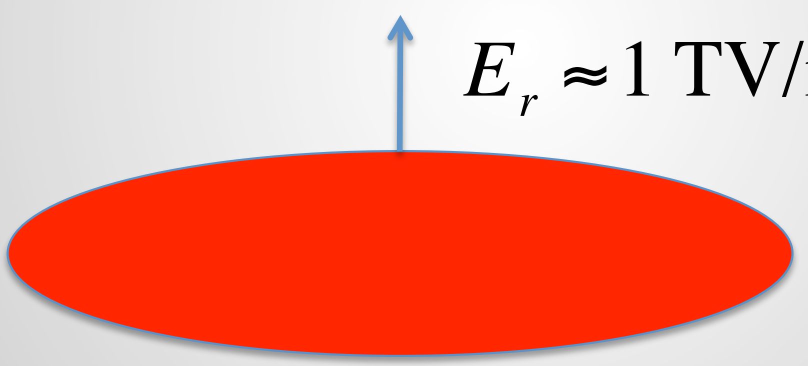
- CER/CTR cases simulated with Lenard-Wiechert
  - Coherent *IR*, sub-cycle pulse (SPARX 1 pC case)
  - Unique source at these wavelengths (~100 MW, peak)
  - Use in tandem w/X-rays in pump-probe
- **Succesful LCLS experiments**
  - New beam diagnostic



QUINDI simulation LCLS case

Physics opportunity: focusing *ultra-short, bright* beams

- 2 fs (600 nm) beam predicted to have I_p=8 kA
- Focus to σ_r<200 nm (low emittance enables…)
- Surface fields $eE_r \approx r_e m_e c^2 I_p / ec\sigma_r$

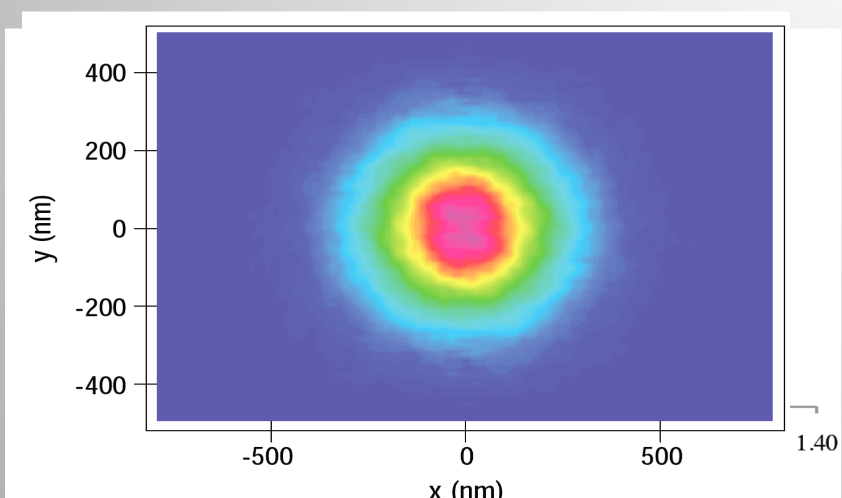


- TV/m (100 V/Å!) in fs unipolar (1/2-cycle) pulse
  - New tool for high field matter interaction
  - Laser *few cycle*, present limit ~100 GV/m

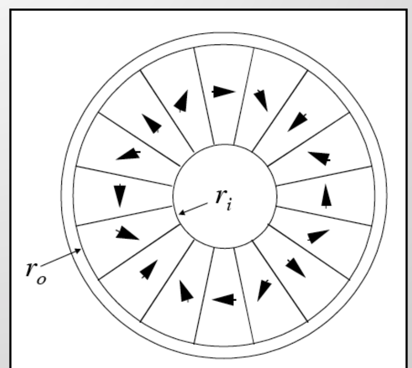
J.B. Rosenzweig, et al., *Nucl. Instr. and Methods A* doi:10.1016/j.nima.2011.01.073 (2011).

How to focus?

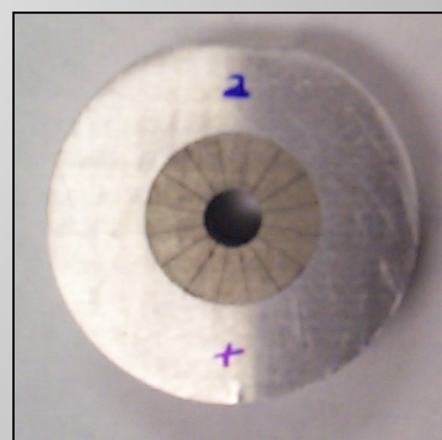
- Very short focal length final focus
- Use ultra-high field permanent magnet quads
  – mitigate chromatic aberrations
  – FF-DD-F triplet, adjust through quad placement
- Developed 570 T/m (!) PMQ fields
  - Need slightly stronger, no problem (Pr gives >1kT/m)



Final beam sizes: ~130 nm



Small aperture PMQ B' =570 T/m

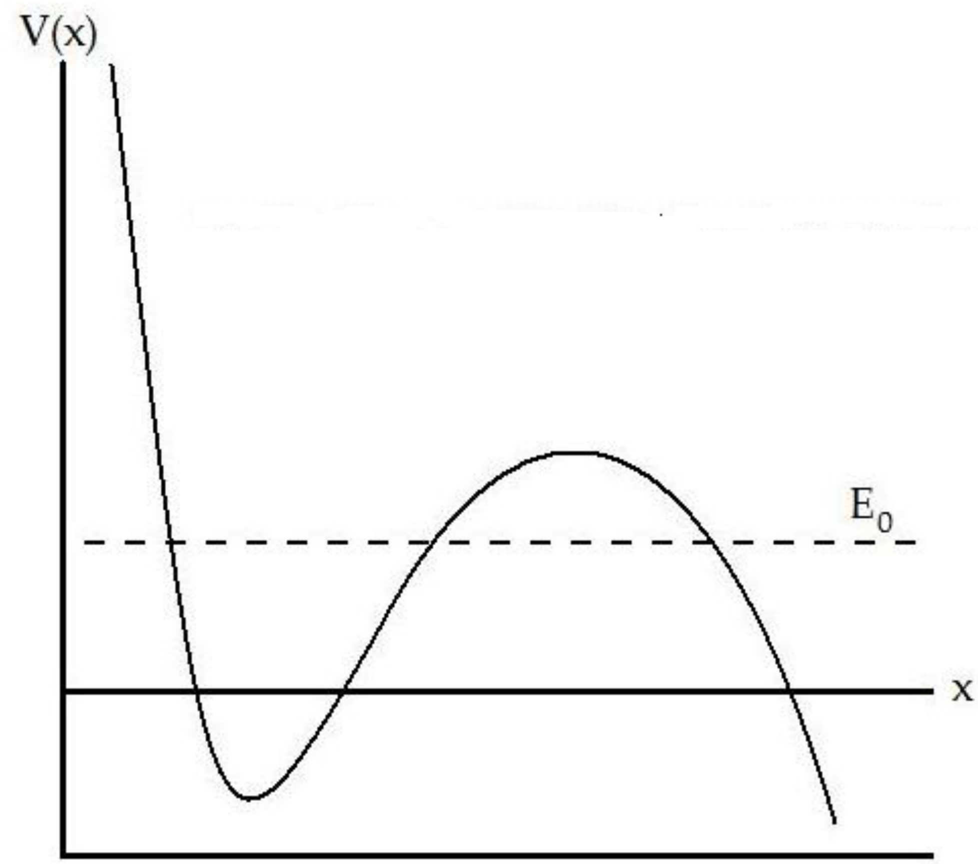


Halbach PMQ as built

J. K. Lim, et al., *Phys. Rev. ST Accel. Beams* **8**, 072401 (2005)

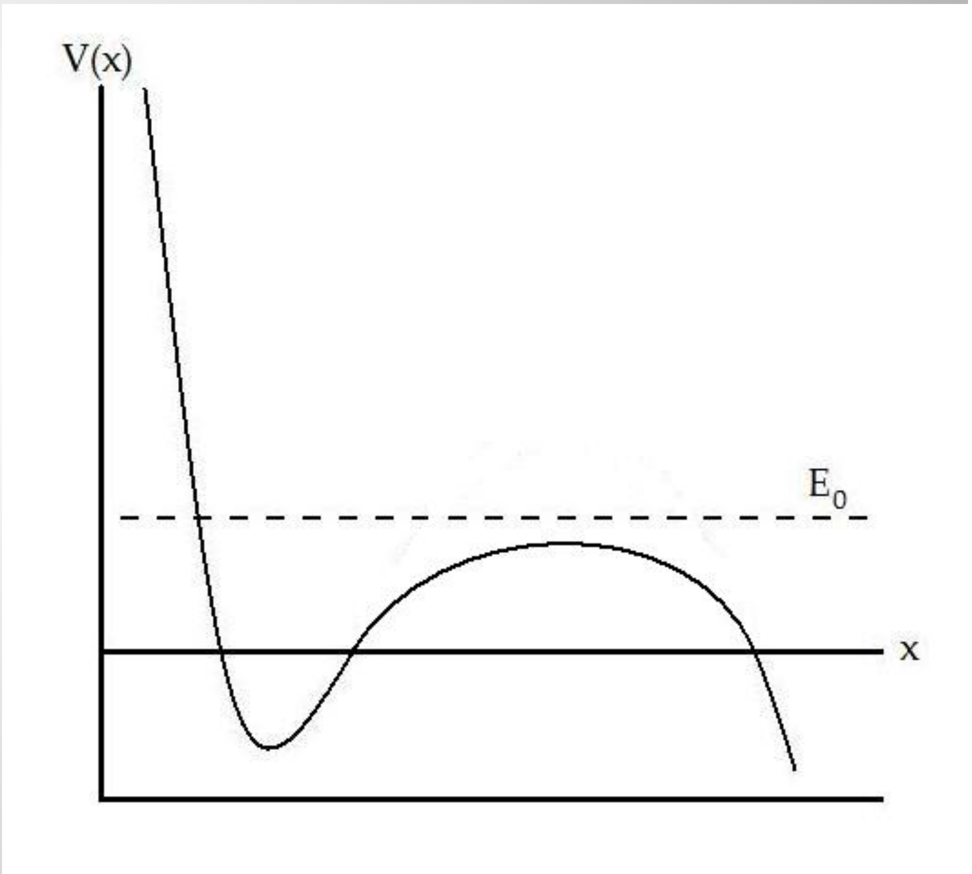
Collective Beam Field-induced Tunneling Ionization

- "Weaker" fields: tunneling
- Regime well understood
  - ADK perturbation theory
  - Developed for lasers
  - ADK-based simulation (OOPIC)
  - Benchmarked to e-beam experiments (FFTB and FACET)



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

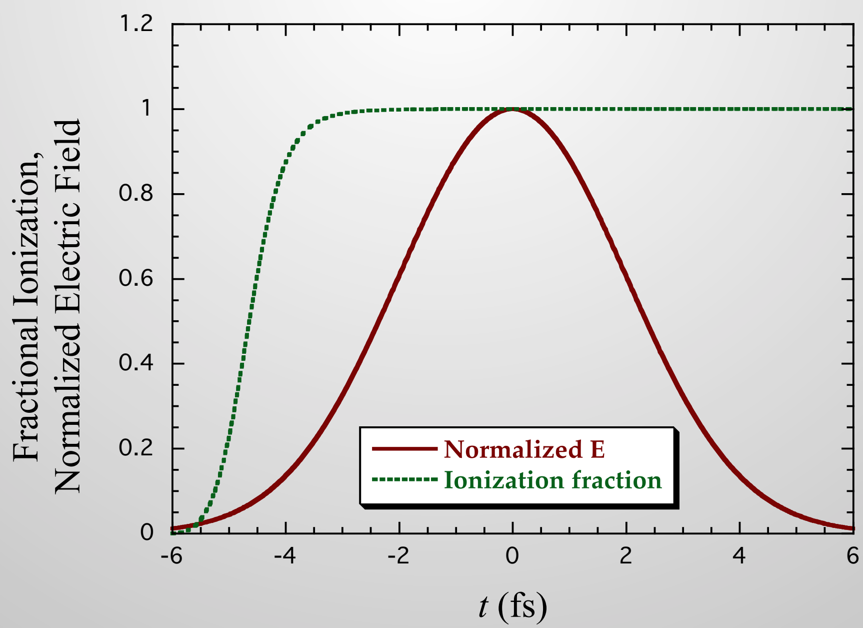
- BSI: e- classically escapes atom
  - Previously only reached experimental by lasers
  - Theory concentrates on lasers
- BSI not well understood
  - *Non-perturbative*
  - Empirical formulas
- **Fundamental atomic physics tool**
  - Unipolar TV/m for the first time
- And, of course, **plasma wakefields**



Does BSI ionization occur in 2 fs?

- 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

D. Bauer and P. Mulser, Phys. Rev. A 59, 569 (1999)

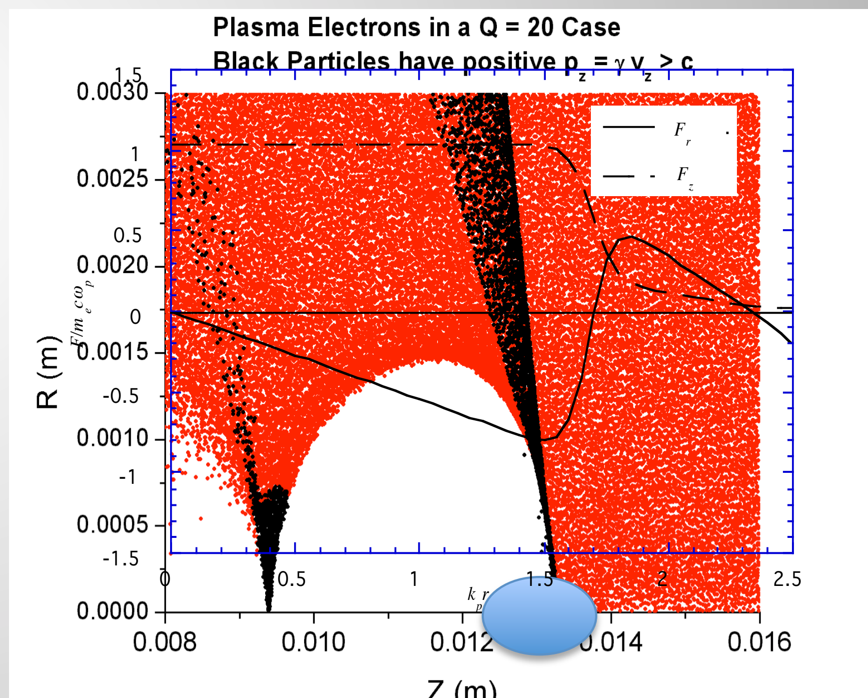


Fractional ionization due to BSI, 800 GV/m peak, 2 fs gaussian pulse

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

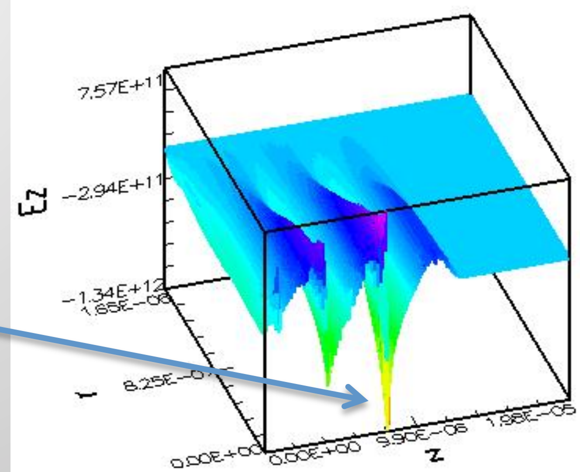
Optimized excitation at LCLS

- 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
- W/2 fs LCLS-like beam at FACET II choose $n_0 = 7 \times 10^{19}\ \text{cm}^{-3}$
- For 20 pC beam, we have $\tilde{Q} = 7$
- Linear "Cerenkov" scaling

$$eE_{z,dec} \cong e^2 N_b \int \frac{n(k)-1}{n^2(k)} dk \Rightarrow e^2 N_b k_p^2 \qquad eE_{z,dec} = \frac{4e^2 N_b}{\sigma_z^2}$$

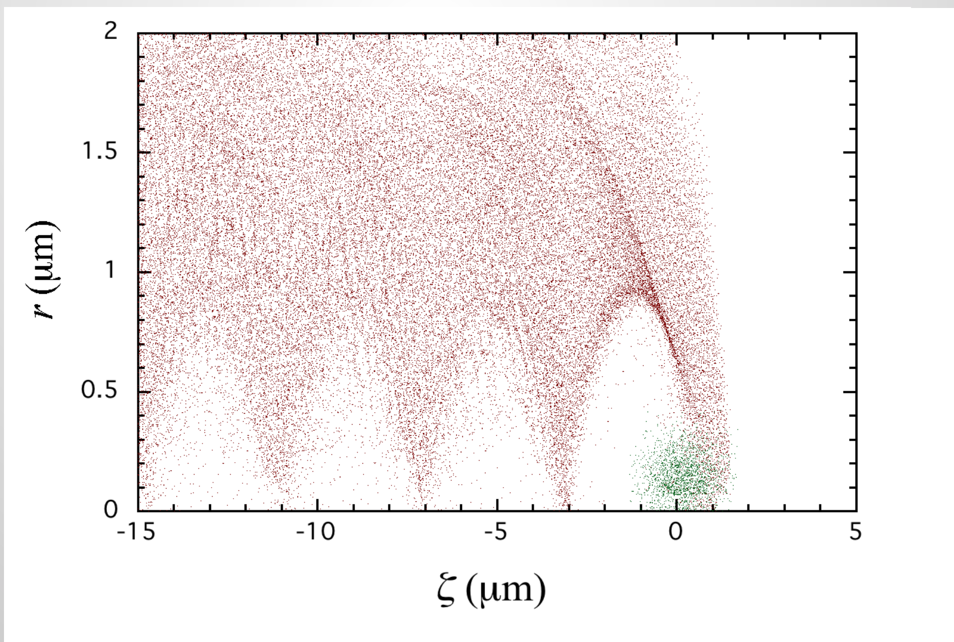
- *1 TV/m fields,* converted E_r)
- Proposal well received at NSF
  - Incorrect submission timing

OOPIC simulation of LCLS case



Beam-field induced ionization in OOPIC

- Need to focus beam to < 200 nm rms
- Radial E-field > TV/m
- Ionization studied in Li, H gas (ADK model)



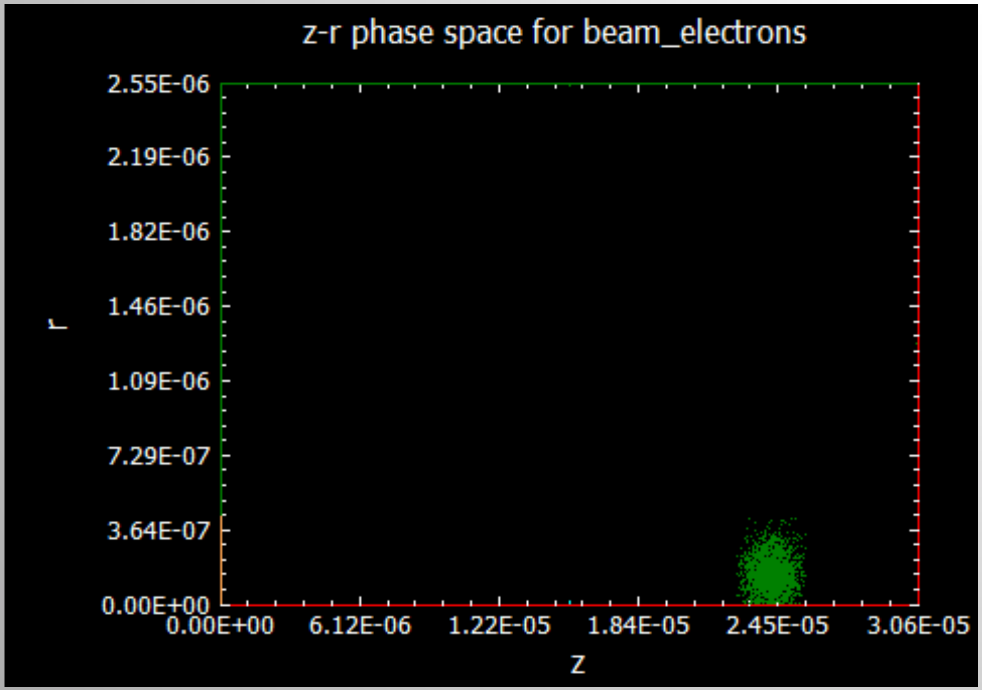
OOPIC study, 3:1.5 ratio hydrogen completely ionized by beam

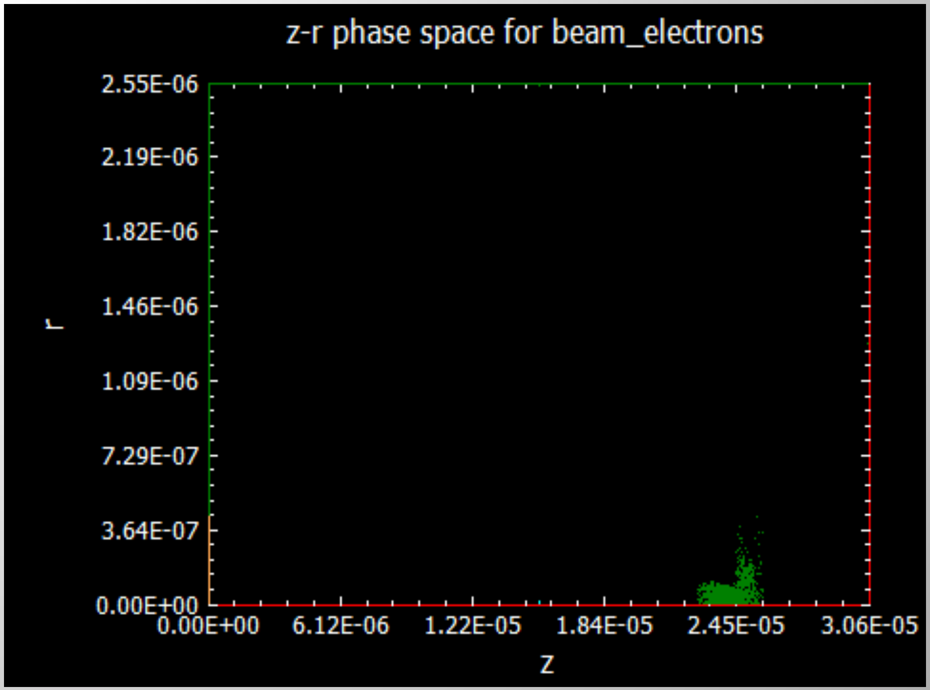
Hydrogen ionization complete inside beam

Complete ionization in Li

Plasma (Ion) Focusing

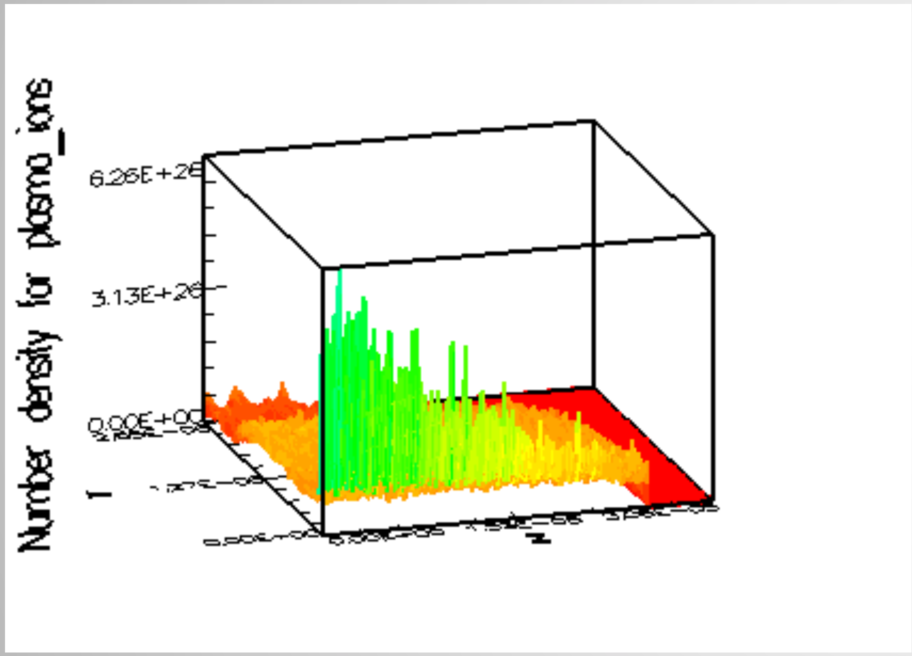
- Beam focuses due to initial mismatch w/gradient
  - Effective gradient is ~1.5 MT/m!
  - Yet higher wakes result
- Ions may in turn be focused by e-beams…



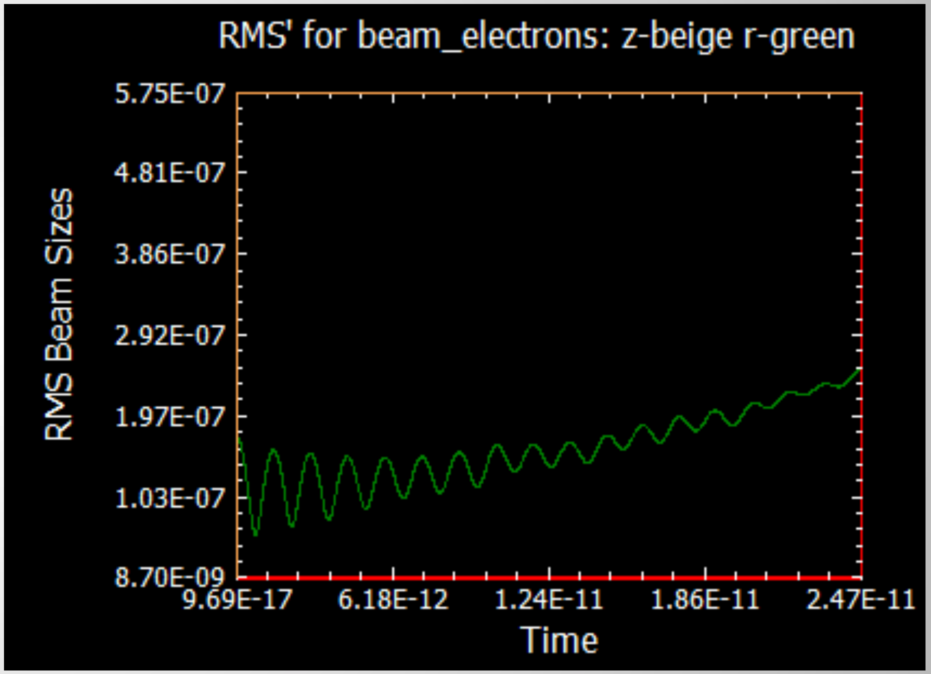


Ion Collapse

- 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)

Experimental implementation

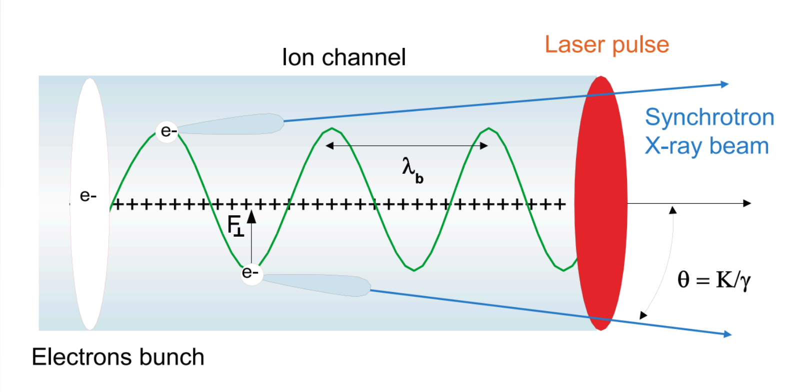
- Beam focusing
  - Few-100 nm beam demands mini-beta PMQs
  - Downstream of LCLS; “turn off” by PMQ placement
    - Alternative is 2nd beamline at switchyard
- Plasma section
  - ~3 atm gas jet, with BSI. Start with tenuous gas
  - Length ~1 mm gives 1 GeV ΔE, “perturbative”
- Beam diagnostics in entirely new regime
  - Longitudinal: coherent edge/transition radiation
  - Transverse: ionization, appearance intensity, betatron

Betratron radiation detection

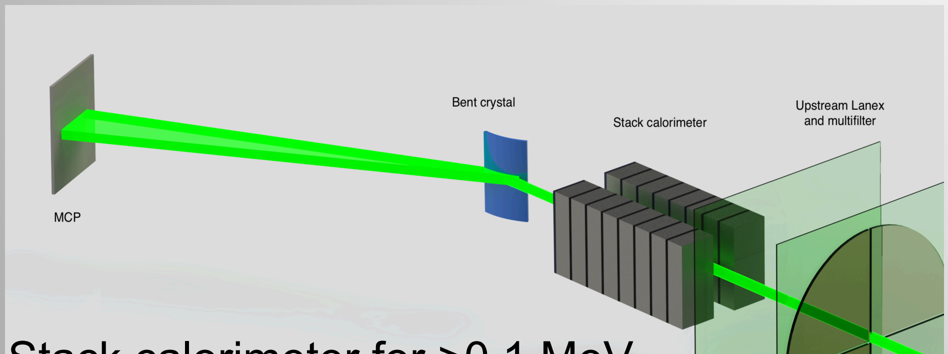
- Ion channel is undulator, with variable amplitude, and K_u

$$K_u = k_\beta \gamma x_0 = 1.33 \times 10^{-2} \gamma^{-0.5} n_0 \left(10^{16}/\mathrm{cc}\right) x_0 (\mu\mathrm{m})$$

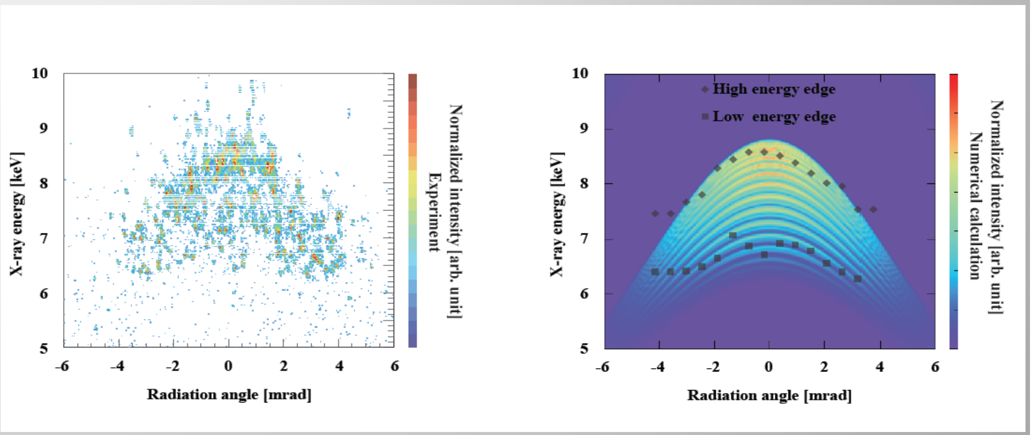
$\lambda_r = \lambda_\beta / 2\gamma^2 \cdot (1 + 0.5K_u^2)$, 1.8 MeV photons



- Very small emittances, narrow line, K_u~0.1
  - Can measure emittance $\Delta\lambda_{rms} = 2\varepsilon_{rms,n}/\gamma$



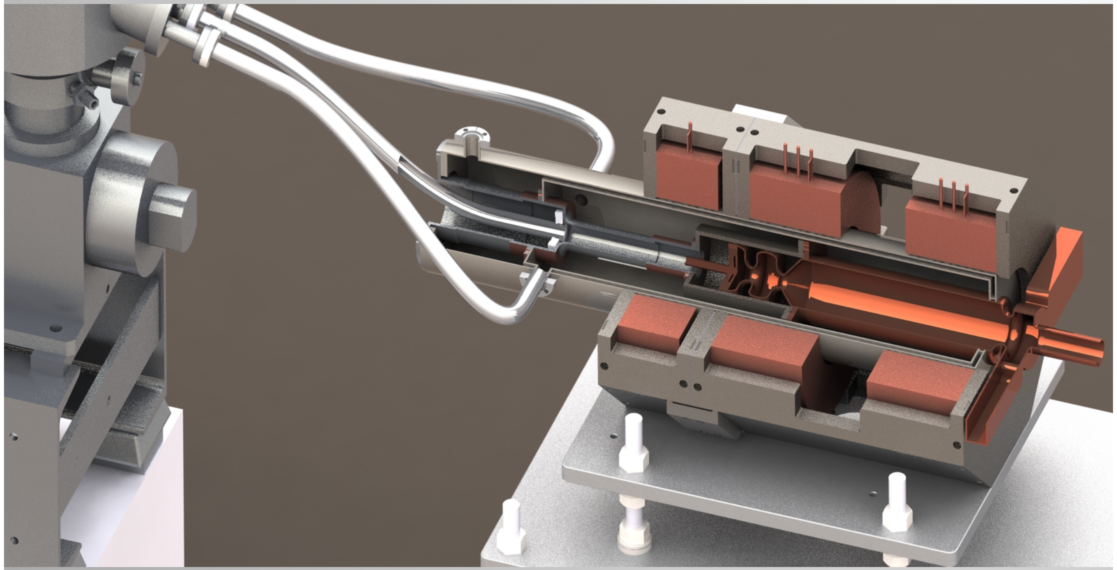
Stack calorimeter for >0.1 MeV
Bent crystal for lower energy X-rays
Boulder-Ecole Poly-UCLA spectrometer collab.

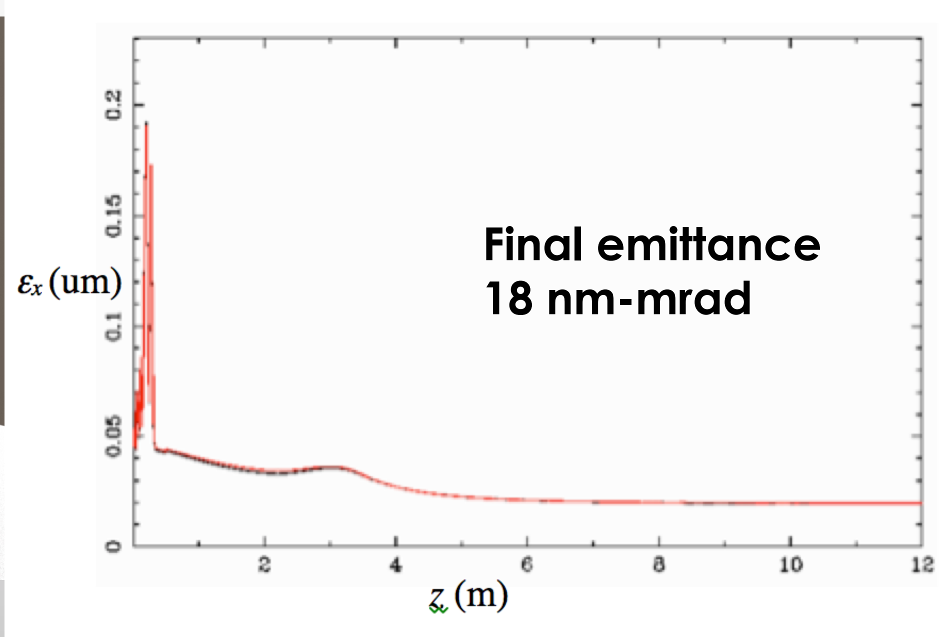


UCLA ICS spectrometer exp't at ATF.

Can we increase the fields?

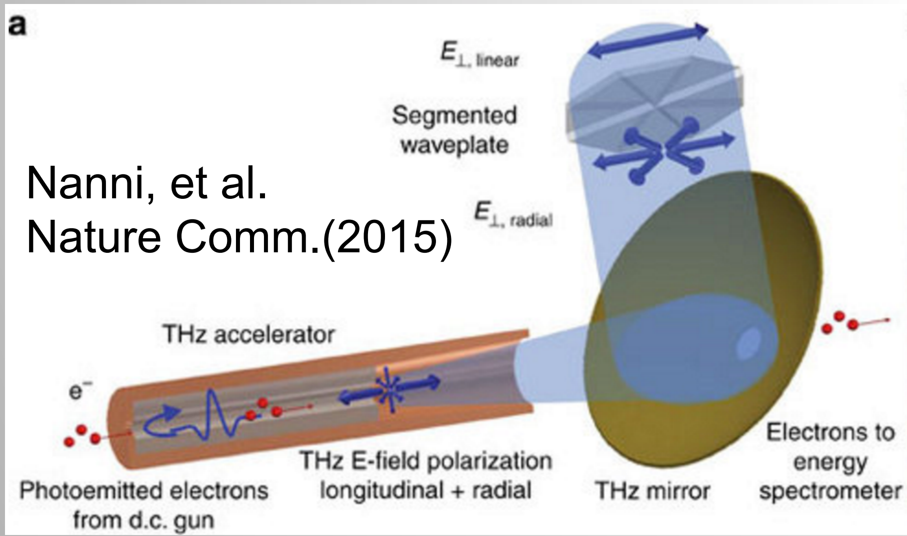
- Next generation cryogenic photoinjectors can produce much higher brightness
- Electric field >250 MV/m
- At 10 pC, ε_n=18 nm simulated
- With 4 atm gas, σ_x=22 nm-rad, $E_{r,max}$~6 TV/m



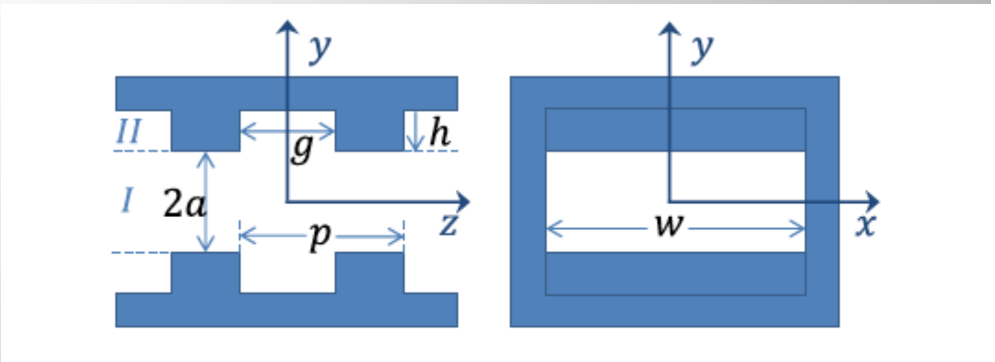


The challenge of compression

- We plan on using 10 pC beam for FEL and PWFA – how to preserve the emittance w/multi-kA
- Preserving ε_n<20 nm-rad a looming challenge
- Proposal: use THz accel. to chirp, weak chicaane then dechirp



Nanni, et al.
Nature Comm.(2015)



Conclusions

- Attosecond regime can be reached with low *Q* e-beams
- Greatly enhanced beam brightness
  - Single spike, compact FELs; enhanced wavelength range
- New regime for beams; coherent optical radiation, ionization, new diagnostics
- Ideal with higher brightness beams at FACET-II
- Enables new frontiers:
  - Ultra-high field atomic physics; 100 V/Angstrom
  - Extreme plasma wakefield accelerator