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

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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

Bunching for high current

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

Recent velocity bunching results from SPARC (INFN-LNF, Frascati)
Original proposal: ultra-short pulses at SPARX (LNF)

- Chicane bunching after velocity bunching
- Use ~1 $\mu$C beam for single spike
  - SS: cooperation length=bunch length
- Short, low emittance beam at final energy 2.1 GeV
  \[ \varepsilon_{nx} \approx 7.5 \times 10^{-8} \text{ m - rad} \quad \sigma_t \approx 600 \text{ attoseconds} \]
- 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 explored at LCLS

Low emittances at LCLS with 20 pC. Diagnostic limited

Emittance near calculated thermal emittance limit
20 pC, 135 MeV, 0.6-mm spot diameter, 400 µm rms bunch length (5 Å)
Measurements and Simulations for 20-pC Bunch at 14 GeV

\[ \sigma_z \approx 0.6 \, \mu \text{m} \]

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)

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

Coherent THz pulses observed


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

- **Successful LCLS experiments**
  - New beam diagnostic

*Graph showing spectral intensity vs. frequency.*

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 $\sigma_r < 200$ 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
  - Laser *few cycle*, present limit $\sim 100$ GV/m

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

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

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:

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

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
- For 20 pC beam, we have \( \tilde{Q} = 7 \)
- Linear “Cerenkov” scaling
  \[ e^2 E_{\perp, \text{dec}, \xi} \frac{4 \pi (k N_b)^2}{\sigma_\xi(k)} \int dk = e^2 N_b k_p^2 \]
- 1 TV/m fields, converted \( E_r \)
- Proposal well received at NSF
  – Incorrect submission timing

\[ n_0 = 7 \times 10^{19} \text{ cm}^{-3} \]
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)
Plasma (Ion) Focusing

- Beam focuses due to initial mismatch w/gradient
  - Effective gradient is $\sim 1.5 \text{ MT/m}$!
  - Yet higher wakes result
- Ions may in turn be focused by e-beams...

![Graphs of z-r phase space for beam_electrons](image)
Ion Collapse

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

- Non-uniform ion density enhancement

- 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 $K_u$

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

$$\lambda_r = \frac{\lambda_\beta}{2 \gamma^2 \left(1 + 0.5 K_u^2\right)}, \text{ 1.8 MeV photons}$$

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

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, $\varepsilon_n = 18$ nm simulated
- With 4 atm gas, $\sigma_x = 22$ nm-rad, $E_{r,\text{max}} \sim 6$ TV/m

Final emittance 18 nm-mrad
The challenge of compression

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

Nanni, et al.  
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