TV/m plasma wakefield accelerator using low charge, ultra-short beam

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Background

- UCLA proposal for ultra-short beams in FEL
  - Single spike operation
  - Breaching attosecond frontier
  - Ultra-high brightness electron beams
- 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 (electronic motion, Bohr period)
    - Femtochemistry, etc.
- 100 fs accessible using standard techniques
- Many methods proposed for the fsec frontier
  - Slotted spoiler; ESASE; two stage chirped pulse
  - Unsatisfactory (noise pedestal, low flux, etc.)
  - Still unproven
- Use “clean” ultra-short electron beam
  - Myriad of advantages in FEL and beam physics
  - Robust in application: XFEL, coherent optical source, PWFA...
The “clean” path:
ultra-low charge electron beam

- Excellent *phase space* quality (\( \perp \) and \( || \))
  - Very low emittance
  - Highly compressible
  - *Unprecedented high brightness*
- Ultra-short high brightness beam in FEL
  - Bunch \( \sim \) cooperation length; *single spike operation*
  - *Short* cooperation length; sub-*femtosecond pulse*
  - Pedestal free, ultra-short X-ray pulse
- Mitigate collective effects dramatically
  - Coherent synchrotron radiation instability (chicane)
  - Undulator beam-pipe wakes
Ultra-high brightness beams: How?

- Brightness \( B = \frac{2I}{\varepsilon_n^2} \propto \frac{Q}{\sigma_t \varepsilon_n^2} \)
- Low Q in injector: shorter \( \sigma_t \), smaller \( \varepsilon \)
- Velocity bunching at low energy, recover \( I \)
- Chicane bunching (1 or 2 stages)
- The rules change much in our favor
  - Low charge makes all manipulations easier
  - Higher brightness gives new possibilities, design application with open imagination...
- Illustrate 1st with original example: SPARX
Photoinjector scaling


- Beam at lower energy is single component relativistic plasma
- Preserve optimized dynamics: change Q, keeping plasma frequency \((n, \text{aspect ratio})\) same
- Dimensions scale \(\sigma_i \propto Q^{1/3}\)
  - Shorter beam...
- Emittances:
  - Space charge, \(\varepsilon_{x,sc} \propto k_p^2 \sigma_x^2 \propto Q^{2/3}\),
  - RF/chromatic aberration, \(\varepsilon_{x,RF} \propto \sigma_z^2 \sigma_x^2 \propto Q^{4/3}\),
  - Thermal emittance, \(\varepsilon_{x,th} \propto T_{th}^{1/2} \sigma_x \propto Q^{1/3}\).
- At low Q, \(\varepsilon_{x,th}\) dominates (Ferrario WP, SPARC/LCLS)

\[
\varepsilon_n \text{ (mm-mrad)} = \sqrt{a_1 Q (\text{nC})^{2/3} + a_2 Q (\text{nC})^{4/3} + a_3 Q (\text{nC})^{8/3}} \propto 0.33 \cdot Q (\text{nC})^{1/3} \text{ (mm-mrad)}
\]

\[
\begin{align*}
  a_1 &= 0.11 \\
  a_2 &= 0.18 \\
  a_3 &= 0.23
\end{align*}
\]
Velocity bunching

- Enhance current at low energy, avoid bending
- Inject near zero crossing
- Apply optimized focusing, manage $\epsilon$ evolution

Longitudinal phase space schematic for velocity bunching
VB example: SPARX (2008), 1 pC

- $\varepsilon$ growth manageable
- 1 order of magnitude compression
- "Thermalized longitudinal phase space; limits subsequent compression
Chicane Compression

- Run off-crest in linac, “chirp” longitudinal PS
- Remove chirp with chicane compressor
  - Complicated by thermal energy spread, CSR

\[
\text{Long beams not easy to compress, large longitudinal } \varepsilon \text{ due to RF curvature}
\]

\[
\sigma_{\varepsilon} \approx \frac{\lambda_{RF} (m) Q(pC)^{1/3}}{P_0 (MeV) \cot(\phi_0)}]
\]

\[
\varepsilon_{\varepsilon, \text{rms}} = \frac{k_{RF} \sigma_{\varepsilon}^3}{\sqrt{2}}
\]
Original goal: 
**single spike XFEL operation**

- **1D dimensionless gain parameter**
  
  \[ \rho_{1D} = \left( \frac{JJ(K_{rms})K_{rms}k_p}{4k_u} \right)^{2/3} \]

- **1D gain length**
  
  \[ L_{g,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{1D}} \]

- **Cooperation length**
  
  \[ L_{c,1D} = \frac{\lambda_r}{4\pi\sqrt{3}\rho_{1D}} \]

- **Single spike operation**
  
  \[ \sigma_{b,SS} < 2\pi L_{c,1D} = \frac{\lambda_r}{2\sqrt{3}\rho_{1D}} \]
Numerical example: SPARX @ INFN-LNF

- Take 2 GeV operation, "standard SPARC undulator", $\lambda_u = 2.8$ cm
- Peak current $I = 2$ kA, $\rho_{1D} = 1.8 \times 10^{-3}$
- Estimate single spike threshold:
  \[
  \sigma_{b,SS} < 0.48 \ \mu m \ (1.6 \ \text{fsec})
  \]
- Note: with ultra-small Q, $\rho$ is enhanced
  - Spike is a bit shorter...
  - FEL gain better
Ultra-short pulses at SPARX

- Scaling indicates use of ~1 pC beam for single spike
- For 1 pC, \( \sigma_z \) only 4.7 \( \mu \)m after velocity bunching
- Use June 2008 version of SPARX lattice
  - compression no longer at end, at 1.2 GeV (Final 2.1 GeV)
- Very high final currents,
  - some CSR emittance growth, for 1 pC \( \varepsilon_{nx} \approx 7.5 \times 10^{-8} \) m - rad
  - Longitudinal tails, higher peak brightness (2 orders of magnitude!)

\[
B = 2 \times 10^{17} \text{ A/m}^2
\]
FEL performance: 1 pC

- Single spike with some structure
- > 1 GW peak power at saturation (30 m)
- 480 attosecond rms pulse at 2 nm
Higher Q SPARX case: 10 pC

- Put back beam power, X-ray photons
- Velocity bunch to 10.3 μm rms
  - Still space dominated charge scaling $\sim Q^{1/3}$
- 1 fs pulse
- Large emittance growth $\varepsilon_n = 7.6 \times 10^{-7}$ m - rad
SPARX FEL at 10 pC

- 10 GW peak FEL power
- Saturation at 20 m (v. high brightness)
- Quasi-single spike
  - Lower brightness=longer cooperation length
  - $4 \times 10^{11}$ photons, good for many applications
Extension to LCLS case

- 1 pC does not give quasi-single spike operation
  - Beam too long, need to scale with $\lambda/\rho$
- Use 0.25 pC (1.5M e$^-$), obtain $\varepsilon_n = 0.033$ mm-mrad
- *Yet higher* brightness; saturation expected in 60 m

$\sigma_E / E = 4 \times 10^{-4}$

Over 350A peak
LCLS Genesis results

Deep saturation achieved

Minimum rms pulse: 150 attosec

Quasi-single spike, 2 GW

$\sigma_\omega \sigma_t \approx 1.1$
Alternative scenario: new undulator for very short $\lambda$ operation

- Use high brightness beam to push to short wavelength
  - LCLS example

- Shorter period undulator
  - Shorter still soon available...

<table>
<thead>
<tr>
<th>$K_u$</th>
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<tbody>
<tr>
<td>$\lambda_u$ (cm)</td>
<td>1.5</td>
</tr>
<tr>
<td>$\beta$ (m)</td>
<td>2-6</td>
</tr>
<tr>
<td>$U$ (GeV)</td>
<td>4-14</td>
</tr>
</tbody>
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Progress at SLAC on low-Q, high brightness beams

- 20 pC case measured
  - Diagnostic limitation
- Excellent emittance after injector
  - No velocity bunching
- Chicane compression
  - As low as 2 fs rms, with some ε growth
Slice Emittance at LCLS: Low Charge Case

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

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

- Horizontal projected emittance measured at 10 GeV, after BC2, using 4 wire-scanners.

- LCLS FEL simulation at 1.5 Å based on measured injector beam and *Elegant* tracking, with CSR, at 20 pC.
Ultra-short beam application: coherent, sub-cycle radiation

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

Total emitted CER spectrum (BNL ATF, UCLA compressor), measured compared to QUINDI. Coherent THz pulses...

Angular distribution of far-field radiation, by polarization: measured in color, QUINDI in contours
Coherent optical-IR sub-cycle pulse

- CER and CTR cases simulated with QUINDI
  - Coherent IR, sub-cycle pulse (SPARX 1 pC case)
  - Unique source at these wavelengths (~30 MW, peak)
  - Use in tandem w/X-rays in pump-probe
  - Would like to try this at LCLS...
Ultra-short beam application: IR wavelength PWFA

- Ultra-high brightness, fs beams impact HEP also!
- 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
  - Linac-style EM acceleration
  - General measure of nonlinearity:

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

- 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 LCLS beam we should choose $n_0 = 7 \times 10^{19}$ cm$^{-3}$
- For 20 pC beam, we have $\tilde{Q} = 7$
- 1 TV/m fields (!)
- Forming collaboration
  - UCLA-SLAC-USC-DESY
What are the experimental issues?

- Length of plasma: ~1 mm
  - 1 GeV energy change, perturbative at beginning
  - Straightforward diagnosis
- Plasma formation
  - 3 atm gas jet
  - Ionization via LCLS X-rays...
  - Beam-induced ionization
- Beam focusing
  - Need sub-μm beam
  - Use strong-field mini-beta insertion
X-ray ionization

- Ionization cross section for 8 keV X-rays in gas is in the kBarn range
- Mean free path of few cm
- With $1E12$ photons and 50 μm X-ray beam, ionization fraction $<1E-4$...
Beam-field induced ionization

- Need to focus beam to $< 1 \, \mu\text{m} \, \text{rms}$ (later...)
- Radial E-field $> \text{TV/m}$
- Ionization studied in hydrogen gas

OOPIC study, 3 atm hydrogen ionized by beam
OOPIC predictions for 3 atm case

~7E19/cc plasma, >TV/m peak wakefield!
Final focusing system

- Need few mm $\beta$-function at plasma
- Use ultra-high field permanent magnet quads
  - mitigate chromatic aberration limits
  - FF-DD-F triplet, adjustable through quad motion
- Developed 570 T/m (!) PMQ fields
Where and when

• Option 1: LCLS beam time proposal
  – Downstream of undulator
  – Competitive
  – Disruptive due to mini-β insert

• Option 2: LCLS bypass line
  – Proposal for test beam (HEP)
  – Possible addition of undulator (BES)
  – Under consideration now, could be fast track

• Option 3: FACET after upgrade
  – Need RF photoinjector
  – Optics not yet established
  – Long lead time...
Use Table-top XFEL undulator?

- LMU MPQ (Garching)-centered collaboration (BESSY, LBNL, UCLA, etc.)
- UCLA collaboration on beam transport and advanced undulator (Pr-based)
- Need short $\lambda_u$ high field undulator for X-rays @ 1 GeV – important for linac-based sources too...

Examine use of undulator at SPARX

*Lase at 6.5 Å (smaller by almost 5)*

Saturation at 500 MW (5E9 $\gamma$’s)

Gain length shortened by 2

Apply with LCLS energy… 0.1 Å?
Lets organize

• Collaboration
  – Based on E169

• Initial explorations with SLAC stake-holders
  – Accelerator people
  – Director
  – Bucksbaum, Stohr

• First experiments in 2011?