Dielectric Lined Waveguides for Beam Acceleration and Manipulation

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Outline

• Beam driven acceleration
  – Longitudinal shaping
    • Alternative shapes for enhanced transformer ratios
    • Investigate temporal laser-shaping to generate such distributions

• Beam manipulation
  – Longitudinal phase space manipulation with self-wake at low energy
    • Microbunching, passive compressor, longitudinal shaping
  – Multiple structures
    • EEHG, acceleration, radiators

• Toward dispersion controlled acceleration in a DLW
  – Tapered dielectric lined waveguides to control phase velocities
Beam Driven Wakefield Acceleration

• Voss-Weiland DESY 1982
• High-impedance medium
  – Dielectric Lined Waveguides (DLW)
    • Cylindrical/Slab symmetric
    • Transmission concerns
    • Low cost
    • Relatively clean (vacuum wise)
  – Plasmas
    • Gas (ionized)/ vacuum concerns
    • Collisions + emittance growth
    • Ease of beam transmission

\[ E(z) = \int_{-\infty}^{z} I(z - z')G(z')dz' \]

\[ G(z) = \sum_{n} \kappa_{n} \cos(k_{n}z) \]
Wakefields and the Transformer Ratio

• Fundamental wakefield theorem: symmetric bunches $R = \frac{E_+}{E_-} < 2$.

• Interested in large accelerating fields and efficient energy transfers.
Overview: Ultimate Transformer Ratio

- For persistent acceleration- require flat decelerating field.
  - Bane ‘85 exponential ramp $R = \sqrt{1 + (\omega T)^2}$
  - Jiang ‘12 double triangle $R = \sqrt{1 + (\omega T - 1)^2}$
  - Difficult to generate such distributions – generally require masks + transverse to longitudinal EEX.
  - Search for smooth/continuous shape with flat decelerating field.
Search for Continuous/Smooth shapes

- Smooth shapes lower emittance requirements in proposed longitudinal shaping techniques
- Coulomb force (space charge) naturally produces smooth shapes.

$$s(z) = \begin{cases} 
  f(z) & z < \frac{\lambda}{n} \\
  f'(\lambda/n)z - f'(\lambda)\lambda/n + f(\lambda/n) & x \geq \frac{\lambda}{n} \\
  0 & \text{elsewhere}
\end{cases}$$
Sinusoidal Ramp

\[ f(z) = az + b \sin(qkz) \]

\[ R = \begin{cases}  
\frac{1}{8} \sqrt{\pi^2(3 - 16N)^2 + 64} \\
\frac{1}{2} \sqrt{\pi^2(1 - 4N)^2 + 4}.
\end{cases} \]

Leads to 2 solutions:
When \( c \) is even, top solution
When \( c \) is odd, bottom solution

4/23/2015
Quadratic Ramp

\[ f(x) = ax^2, \]

\[ R = \sqrt{1 + \pi^2(2N - 1)^2}. \]
• Previous description of $R$ are usually not normalized to a specific charge.

• Normalizing each proposed shape yields interesting results:

$$Q = \int_0^{N\lambda} dz I(az),$$
Longitudinal Shaping Techniques

- Mask-based techniques
  - Transverse to longitudinal
    - Emittance exchange (EEX)
    - Chicane based
- Beam manipulation with RF
  - Experiment done at FLASH
- Investigate alternative techniques
Temporal Laser Shaping

• Longitudinal laser-shaping
  – Generate longitudinal electron distribution out of RF gun.
  – Large accelerating fields (e.g. S-Band) can preserve relatively high charge density distributions.
  – Support high-repetition rates
  – Use compressor at high-energy to scale the distribution if necessary.
Laser Shaping Continued

• Investigate polynomial (right \( I = a z^2 \)) and exponential laser profile pulses

• Tunable parameters
  – Laser (length, shape, spotsize)
  – Charge
  – Acceleration gradient
Passive manipulation: Recent results

- Recently proposed/demonstrated passive applications:
  - De-chirper
    - P. Emma et al. PhysRevLett.112.034801
    - S. Antipov et al. PhysRevLett.112.114801
  - Multi Bunching: S. Antipov et al. PhysRevLett.111.134802
Self-Wake Interactions at Low Energy

• Photo-Injector Source:
  – ~ 100 Amp currents.
  – < 10 MeV energy out of gun (L-Band(1.3GHz - 35 MV/m) vs S-Band(2.856 GHz – 140 MV/m), X...), energy spread.
  – Emittances < 5 µm for S-Band. Ideal for fitting into smaller structures.

• Ballistic bunching, shaping+

\[ R_{56} \approx -\frac{D}{\gamma^2} \]
Numerical Simulations with ASTRA

- Particle tracking code with space charge
- Use 2+1/2 D – cylindrical symmetry.
- 100k macro particles,
- 200 long. bins, 7 rad. bins.
- Use Green’s function “WAKE” ASTRA module.
- Use offline software to calculate the bunch form factor (BFF)

\[ \tilde{F}(\omega) = \frac{1}{N^2} \left( \left| \sum_{i=1}^{N} \cos \left( \frac{\omega z_i}{c} \right) \right|^2 + \left| \sum_{i=1}^{N} \sin \left( \frac{\omega z_i}{c} \right) \right|^2 \right) \]
Density modulation at 1 THz

- S-Band Gun
- DLW parameters \((a, b, \varepsilon, L)\) = \((350 \, \mu\text{m}, 363 \, \mu\text{m}, 5.7, 11 \, \text{cm})\)
1THz Continued..

• Fitting into 11 cm structure OK (84 % transmission).
• DLW length change impact.
• Can we do better than BFF=0.2?
  – Energy correlation in LPS
    • Solution 1: Longer bunch
    • Solution 2: Lower the frequency
500 GHz DLW – (350 µm, 393 µm, 5.7)

- Large harmonic content at maximum compression.
- Higher mode suppression by under/over compressing the bunches.
L-Band case study

• Larger emittance
  – Larger structures
  – Lower frequencies

• Lower energy
  – Shorter bunching length for same energy modulation
  – More space charge effects
Passive Compressor

- $L \sim \lambda$ – Single peak.
- Peak current limited by energy spread.
- Scan various wavelengths and record peak current.
- For L-Band case, this corresponds to a peak current of $\sim 12$ kA (7.1%).
- Scalable for higher charge / large structures $a=650 \, \mu$m
Passive Compressor for beam-driven applications

- Bunch larger portion of the bunch (50%)
- Extremely scalable: higher charge $\rightarrow$ longer bunches $\rightarrow$ larger structures.
- Details: Red trace: immediately after structure, blue trace 1.2 m (1.13 m bottom) downstream.
- $(a, b, e, L) = (1 \text{ mm}, 1.05 \text{ mm}, 5.7, 5 \text{ cm})$ corresponding to $\lambda_0 = 1.948 \text{ mm}$
Longitudinal Shaping with DLW

- Larger wavelengths ($\lambda \gg L$)
  - Bunch shaping
  - Passive bunching
  - De-chirper/Linearizer

- Ramped bunch for high transformer ratio acceleration.
  - Here for (165 µm, 197 µm, 5.7)
  - $R = 7.3$ (Theoretical max 9.3)
Cascaded Passive Manipulation

• Can this be done with non-ultra-relativistic beam and passive structures?

\[ k_E = nk_1 + mk_2 \]

[Image of a diagram showing cascaded passive manipulation with beam and laser interactions.]
EEHG with DLWs

Before (red) and after (blue) DLW #1

Overbunched LPS before DLW #2

Second energy modulation from DLW #2

After subsequent drift, EEHG occurs
DLW-EEHG outlook

• Relatively cheap
• Capable of < 50 fs electron bunch formation
• Second structure frequency limited by first.
• Self wake requires relatively large bunch charge/currents
• Technique could do better at higher energy (IPAC15).
Merging concepts for Acceleration

- DLWs in series, bunch and accelerate
- DLW dimensions limited by beam
- Total energy gain limited by transformer ratio
Compact X-Ray source

- S-band test case:
  - $E^+ \approx 111$ MV/m
  - $E^- \approx 43$ MV/m
  - $R = 2.6$
Dispersion Controlled Acceleration in DLW

• Acceleration in free space
  – Lawson-Woodward overcome with $a_0 \gg 1$ (S. Carbajo et al. 2015).

• THz acceleration in DLW
  – Sustains modes with phase/group velocities $< c$
  – Capable of large acceleration gradients (E. Nanni et al. 2014)
Primitive look at DCA

- 1 electron experiencing constant acceleration gradient of 100 MV/m.
- Solve dispersion relations backwards ($v \rightarrow a$).

\[ 0 = k_{x1}^2 \sin^2(k_{x1}t) \sin(k_{x2}(a - 2t)) - e^2 k_{x2}^2 \cos^2(k_{x2}(a - 2t)) \]
\[ -2e k_{x1} k_{x2} \sin(k_{x1}t) \cos(k_{x2}(a - 2t)) \]
\[ 0 = k_{x1} \sin(k_{x1}t) \sin(k_{x2}(\frac{a}{2} - t)) - e k_{x2} \cos(k_{x2}(\frac{a}{2} - t)) \cos(k_{x1}t) \]

**LSM Modes**

\[ k_{x1}^2 = \frac{\omega^2}{c^2} - k_z^2 - k_y^2 \]
\[ k_{x2}^2 = \frac{\omega^2}{c^2} - k_z^2 - k_y^2 \]

\[ \beta_z = \frac{cqEt}{\sqrt{(cqEt)^2 + E_0^2}} \]
\[ z(t) = \frac{1}{qE} \sqrt{(cqEt)^2 + E_0^2} \]
Primitive look at DCA cont.

- Hyperbolic-like diameter
  - Analytical solution?

- Additional things to consider:
  - Cylindrical geometry
  - Mode coupling
  - Group *and* phase velocity matching?
  - Full simulation required (PIC?)
  - Machineable (CNC) or 3D print?
Summary

• Beam driven techniques
  – Investigated alternative smooth ideal transformer ratio shapes
  – Proposed laser-shaping technique to generate quadratic-ramp

• Beam manipulation at low energy
  – Passive compression (large peak currents, charge densities, scalable)
  – EEHG
  – Acceleration at low energy for X-ray source

• Dispersion controlled acceleration
  – Can we mitigate phase slippage in a low energy THz-based accelerator with a tapered DLW? –THz Gun
Thank you to Daniel Mihalcea, Harsha Panuganti, and especially Philippe Piot for support.
Thank you to NIU for fellowship awards and stipend support.
This work was supported by the Defense Threat Reduction Agency, Basic Research Award # HDTRA1-10-1-0051, to Northern Illinois University and by the Department of Energy contracts No. DE-FG02-08ER41532 and No. DE-SC0011831 with Northern Illinois University.

QUESTIONS & DISCUSSION
Experimental setup

• Tilted wavefront THz generation using LiNbO with EO detection
• Setup allows for a target (DLW)
• Currently investigating slab-symmetric DLW in preparation for ASTA experiment.
• First results promising; comparing with simulation for IPAC15.
THz experiment continued

- First data recently taken, experiment in progress.
- Goals: investigate THz dispersion in DLWs with various geometries (possible applications to acceleration and beam manipulation).
RADIATION

• Radiation extraction
  – Using two DLWs of same (or higher harmonic) frequency.
  – Efficient
\[ V_-(z) = \int_0^z s(z') \omega(z-z')dz' = \begin{cases} 
\lambda \left( \frac{2\pi \lambda}{\lambda^2 - 1} \right) \left( a \cos \left( \frac{2\pi z}{\lambda} \right) \right) & z > \lambda/2 \\
\lambda \left( a \cos \left( \frac{2\pi \lambda}{\lambda^2 - 1} \right) \right) & z < \lambda/2 
\end{cases} \]

\[ V_-(z) = \int_0^z s(z') \omega(z-z')dz' = \begin{cases} 
\frac{a \lambda^2 (2\pi z - \lambda \sin \left( \frac{2\pi z}{\lambda} \right))}{2\pi^3} & z < \lambda/n \\
\frac{a \lambda^2 (2\pi - n \lambda \sin \left( \frac{2\pi z}{\lambda} \right) + \sin \left( \frac{2\pi z}{\lambda} \right)))}{2\pi^3 n} & z > \lambda/n.
\end{cases} \]
Passive Compressor (Central Bunching)

- $L = \lambda \rightarrow \text{“Central-bunching”}$
- High-charge compression
- For S-Band case, this corresponds to \(\sim 55.8\%\) of the bunch in \(\sim 100 \, \mu m\).
- Extremely scalable: higher charge $\rightarrow$ longer bunches $\rightarrow$ larger structures.
- Details: Red trace: immediately after structure, blue trace 1.13 m downstream.
- \((a, b, e, L) = (0.8 \, mm, 0.85 \, mm, 5.7, 10 \, cm)\) corresponding to $\lambda_0 = 1.774 \, mm$
EEHG with DLWs

• Undulator+Laser ➔ DLW
• Chicane ➔ Drift
• Simulation:
  • (top) bunch before (red) and after DLW (a, b, e, L) = (0.4 mm, 0.43 mm, 5.7, 10 cm) (0.6 THz)
  • (bottom) overbunched before DLW2 (a, b, e, L) = (0.5 mm, 0.55 mm, 5.7, 5 cm) (0.4) THz
EEHG with DLWs Cont.

• (top) after DLW2
• (bottom) At maximum bunching BFF $\sim 0.08$