Beam Dynamics with Self-Wakes in Dielectric-Lined Waveguides

François Lemery, Philippe Piot and PITZ team:

G. Amatuni†, P. Boonpornprasert, Y. Chen, J. Good, B. Grigoryan†, M. Krasilinikov, O. Lishilin, G. Loisch, S. Philipp, H. Qian, Y. Renier, F. Stephan,
Acknowledgments

EAAC17: “A conference so nice that it doesn’t make sense!”

Thanks to:

Franz Kaertner for useful discussions and support.

Ralph Assmann and organization committee for the spectacular workshop!

My new colleagues for very fruitful discussions and help preparing for the talk: Thomas, Willi, Frank, Daniel, Maria, Angel, Jun, Andy, Barbara, Ulrich.

My excellent Ph.D. adviser Philippe Piot

And most importantly the fantastic PITZ team for their beyond excellent experimental efforts to realize this work! We are indebted!
Introduction

- Charged particle beams interact with their environment and produce wakefields, generally in accelerators wakefields are bad, but sometimes they can be good, too.

High impedance mediums e.g. dielectric-lined waveguides, corrugated structures and plasmas are used to generate large wakefield amplitudes.

The wakefield can be calculated from the convolution of the current profile and the Green’s function:

$$ E(z) = \int_{-\infty}^{z} I(z - z')G(z')dz' \quad G(z) = \sum_{n} \kappa_n \cos(\kappa_n z) $$
Applications

- Efficient beam-driven acceleration between drive and witness bunch, Voss&Weiland 1972. May be useful in future TeV colliders with enhanced transformer ratios.

- Beam manipulation applications:
  - Linearizer/dechirper for improving peak currents or reducing energy spreads
  - Multibunching for e.g. THz generation applications

DLW overview

- Dielectric-lined waveguides (DLW)
  - Around since 60s, applications to communication and data transfer.
  - Wakefield application came in mid-to-late 1980s, see W. Gai.
  - First experiments in early 90s.
  - Fundamental mode is a deflection mode which has limited their use for e.g. collider applications.

- Argonne National Lab recently demonstrated 100 MV/m from drive to witness beam! See M. Conde talk.

In high energy regime, $k_1 \to 0$ and fields are uniform.

\[
\begin{align*}
  k_1 &= \omega \sqrt{\frac{1}{c^2} - \frac{1}{v_p^2}} \\
  k_2 &= \frac{\varepsilon_r}{\varepsilon_r} \frac{1}{c^2} - \frac{1}{v_p^2} \\
  k_z &= \frac{\omega}{v_p}.
\end{align*}
\]

\[
E_z = \begin{cases} 
  B_1 J_0(k_1 r) e^{i(\omega t - k_z z)} & 0 \leq r < a \\
  B_2 F_{00}(k_1 r) e^{i(\omega t - k_z z)} & a \leq r < b
\end{cases}
\]

\[
E_r = \begin{cases} 
  \frac{-ik_z}{k_1} B_1 J'_0(k_1 r) e^{i(\omega t - k_z z)} & 0 \leq r < a \\
  \frac{-ik_z}{k_2} B_2 F'_0(k_2 r) e^{i(\omega t - k_z z)} & a \leq r < b
\end{cases}
\]

\[
H_\phi = \begin{cases} 
  \frac{-i\omega \varepsilon_0}{k_1} B_1 J'_0(k_1 r) e^{i(\omega t - k_z z)} & 0 \leq r < a \\
  \frac{-i\omega \varepsilon_0}{k_2} B_2 F'_0(k_2 r) e^{i(\omega t - k_z z)} & a \leq r < b
\end{cases}
\]
Self-Wake Interactions at Low Energy

- Photo-Injector Source:
  - ~ 100 Amp currents.
  - < 10 MeV energy out of gun (L-Band(1.3GHz - 60 MV/m) vs S-Band(2.856 GHz – 140 MV/m), X...), energy spread.
  - Emittances < 1 µm for S-Band. Ideal for fitting into smaller structures.

- Ballistic bunching, shaping+

- No CSR

\[ R_{56} = \frac{Z_{\text{drift}}}{\gamma^2} \]
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).
• 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 $a=650$ µm
Passive Compressor for beam-driven applications

- Bunch larger portion of the bunch (50%)
- Extremely scalable: higher charge → longer bunches → 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 ($\lambda >> L$)
  - Bunch shaping
  - Passive bunching
  - De-chirper/Linearizer

- Ramped bunch for high transformer ratio acceleration.
  - Here for (165 $\mu$m, 197 $\mu$m, 5.7)
  - $R = 7.3$ (Theoretical max 9.3)
Experiment at PITZ

Setup allowed for precise beam alignment and transmission through DLWs:

- DLWs holder equipped with YAG:Ce screens
- Gun quad system improved beam symmetry and enabled full transmission
- Two steerers between gun and DLW.
- PITZ’ flat-top pulses improved results significantly.

- Coated DLW ($\lambda = 1.03 \, mm$)
  
  $(a, b, L, \epsilon_r) = (450 \, \mu m, 550 \, \mu m, 5 \, cm, 4.41)$

- Uncoated DLW ($\lambda = 1.60 \, mm$)
  
  $(a, b, L, \epsilon_r) = (750 \, \mu m, 900 \, \mu m, 8 \, cm, 4.41)$
Experiment at PITZ

- Demonstrated the formation of ~ps bunch trains at ~6 MeV with resolution limited peak currents up to ~150 A

- Directly measured the longitudinal phase space downstream of the DLW structure

- Passed a bunch train with up to 200 bunches per pulse through the structure and monitored energy modulations

- No dynamical effects observed.
Control of longitudinal phase space

• Booster phase provides a knob to control the longitudinal phase space correlation

• Possible applications as:
  • an injector for multicolor radiation source (e.g. FEL)
  • Time resolved ultrafast electron diffraction (UED) single-shot!
Grazie per l'attenzione!