ASSESSMENT OF OPPORTUNITY FOR
A COLLINEAR DIELECTRIC WAKEFIELD ACCELERATOR FOR A SOFT X-RAY FEL FACILITY

Many hurdles to overcome as you will see…

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Collinear acceleration in a hollow dielectric channel or corrugated wall waveguide

- Low cost device (likely)
- Potential for:
  - high field gradients
  - high wall plug power efficiency
  - high bunch repetition rate

A concept of a multi-user FEL facility

Based on:
High repetition rate SRF linac

Collinear Wakefield Accelerator (CWA)

- Low E spreader
- Up to 100 MV/m
- CWA imbedded in FODO lattice
- Tunable $E \sim$ a few GeV
- Tunable $I_{pk} > 1$ kA
- Rep. rate $\sim 50$ kHz/FEL

Compact Inexpensive Flexible
Beam by design: beam shaper and why we need it

Road map to a high energy gain acceleration: transformer ratio\(^1\)

\[
R = \frac{E^+}{E^-} = \frac{\text{(Maximum field behind the drive bunch)}}{\text{(Maximum field inside the drive bunch)}}
\]

Goal is to extract maximum energy from drive bunch, up to 80%

Drive bunch shaping using emittance exchange EEX*

Argonne Wakefield Accelerator (AWA)

After EEX

Transverse particle distribution after mask

- ~25 kW is deposited on mask at low energy 5 MeV, i.e. below threshold energy for isotope production

Talk by J. Power, this workshop

Drive bunch shaping using photocathode laser \(^1\)

... was proposed to remove significant quadratic energy chirp at the end of the FERMI FEL linac

2) Zholents and Zolotorev, ANL/APS/LS-327, (2011)
Drive Bunch Beam Breakup Instability

Examples of longitudinal and transverse wakefield functions

Cumulative collective instability arises from continuous exposure of tail electrons to transverse wake field*

Balakin-Novokhatsky-Smirnov (BNS) damping of BBU

- Use FODO
- Produce “chirp” in the betatron tune along the electron bunch using the energy “chirp”, and
- Force tail to oscillate faster than head, thus averaging the impact of transverse wake fields.

**Illustration for Dielectric Wakefield Accelerator (DWA)**

- **Transverse oscillation of particles of a chirped beam**
- **Particles of different energies have different oscillation periods in the FODO lattice**

Initial energy chirp ~15 % (peak-to-peak)
Maximum energy gain is defined by quadrupole strength

Wakefield accelerator

$$W_z \sim \frac{Q}{a^2}$$

$$W_\perp \sim \frac{Q}{a^3}$$

Drive

Main

Tapered quadrupole gradient

Quadrupole wiggler

Two quadrupoles back-to-back

NdFeB

Soft iron

5 cm

N. Strelnikov, I. Vasserman

Dielectric channel imbedded into quadrupole wiggler

High gradient permanent magnet quad

- Bore radius = 1.5 mm.
- Peak gradient = 0.96 T/mm.
- Gradient integral / length = 0.9 T/mm.
- Weight = 300 g.
- Magnetic force between top and bottom parts = 30.5 kg.

the drive beam tail decelerates more, develops more lagging, and sees the wake’s accelerating field.
Problem mitigation

- Move main bunch to second maximum *(can be difficult if done using the mask)*

- Make adaptive frequency channel and always keep main bunch at or near to the maximum *(easy)*

- Use drive bunch with higher energy *(affects facility cost and energy efficiency)*

\[ \omega_1 < \omega_2 < \omega_3 \]
Result of tracking for 8nC drive and 250 pC main bunch

After 2 m  \(E_{in}=400\) MeV

\[
\begin{align*}
\rho &= \gamma \beta \\
TM_{01} \text{ freq } &= 299.7 \text{ GHz}
\end{align*}
\]

\[
\begin{align*}
\text{current} & \quad \text{wake} \\
z (\text{mm}) & \\
t
\end{align*}
\]

After 20 m  \(E_{out}=2.0\) GeV

\[
\begin{align*}
\rho &= \gamma \beta \\
TM_{01} \text{ freq } &= 336 \text{ GHz}
\end{align*}
\]

\[
\begin{align*}
\text{current} & \quad \text{wake} \\
z (\text{mm}) & \\
t
\end{align*}
\]
Tolerances

- **Misalignment of FODO quadrupoles (or trajectory)** < 1 µm
  - 5 µm initial orbit offset
  - Random misalignment rms errors
    - 2 µm
    - 1.75 µm
    - 1.5 µm
    - 1.25 µm
    - 1 µm
    - 0.75 µm
  - No particle losses in the case of correlated variation with amplitude of 2 µm and period > 0.3 m.

- **Straightness of the dielectric channel waveguide**: better than 10 µm
  - Maximum amplitude is 10 µm and the period is varied

**Figure:**
- **Lost particles (%)** vs. **z (m)**
  - 0 to 80% on the y-axis
  - 0 to 25 m on the x-axis

**Histogram:**
- **Particle loss (%) at 20 m**
  - Period (cm) on the x-axis
  - 0 to 40% on the y-axis
### FEL simulations (illustration)

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Undulator period, cm</td>
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<tr>
<td>Undulator parameter, K</td>
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<td>Energy, GeV</td>
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<td>RMS energy spread, %</td>
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<td>Pierce parameter</td>
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<td>X-ray wavelength, nm</td>
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<td>Peak power, GW</td>
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<tr>
<td>Bandwidth, %</td>
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</table>

**Graphs:**
- Energy vs. Undulator length
- Current vs. ct
- Power vs. t (fs)
- X-ray wave length vs. ct
- Bandwidth vs. Delta omega over omega
The initial goal is to build a 1 m long accelerator unit and test it in LEUTL tunnel using APS injector linac.

A concept of a dual quad module*

*) courtesy of S. Doran
Summary

- High repetition-rate, soft X-ray FEL user facility
  - 10 CWAs linacs driven by a single 400 MeV SRF linac
  - 10 FEL lines @ 50 kHz bunch repetition rate
  - Compact, inexpensive, and flexible

- Progress
  - Drive bunch shaping (triangular + quadratic component)
  - Control of beam breakup instability
    - Quadrupole wiggler, adaptive frequency channel
  - Small “main bunch” energy spread

- Future development
  - improving transmission efficiency through the mask – critical
  - space charge effects
  - beam-based trajectory correction - potential showstopper
  - modular design: quadrupole wiggler, vacuum chamber, cooling - critical
  - break sections: BPMs, rf couplers, correctors, etc.
Thank you for your attention