Considerations for seeded FELs in ERLs

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Outline

• Rationale for using ERL driver
• System requirements
• Expected performance
• Notional test implementation
• Conclusions: issues/challenges
1st Reaction: “Why Bother?”

- Seeded systems \(\sim 1\ \text{kHz}\)
  - \(\Rightarrow 1\ \mu\text{A} \text{ at } 1\ \text{nC}:\) only 1 kW beam at 1 GeV;

  However… There are mitigating factors:

- Seed rep rates are expected to increase
  - 1 kHz \(\rightarrow\) 10 (100) kHz anticipated
  - self-seeding schemes forthcoming

  will raise required drive beam power

- ERL can simultaneously service *multiple* FELs – including those with different architecture (xfelo, SASE) & requiring higher drive beam power

- Cost trade isn’t between straight linac & ERL, its between recirculator & ERL
More Nuanced Consideration

• Must consider
  – Goals of facility (numbers & requirements of users, provision for simultaneous service, monochromatic/technicolor operation,…)
  – Detailed cost optimization
  – Anticipated technology development over facility lifetime (esp. seed laser, self-seeding methods)

• *If*
  – the machine is to serve multiple simultaneous users, at different wavelengths, with useful gymnastics (pump/probe, etc), and multiple types of FEL, or
  – performance evolves to provide high-rep-rate seeding, *use of seeded FELs in ERLs becomes interesting*
Calibration: Machine Architectures

• Recirculating linacs
  – SRF is expensive, beam transport is cheap:
    1 pass < cost optimum < \infty \text{ passes}
  • multipass engenders:
    – beam dynamic sensitivity (beam quality),
    – operational complexity

• ERLs:
  – RF drive is expensive, beam transport is cheap
  – Cost optimum occurs when
    cost of single (return) arc < cost of linac RF power
  • 1 \text{nC} \times 1 \text{MHz} \times 1 \text{GeV} = 1 \text{MW} \Rightarrow 10 \text{ M$}$
  • Additional operational complexity
ERL-Specific “Features”

- Cost optimization a bit complex
  - ERLs can drive several FELs – potentially at same time, so $($/FEL) \propto (1/\text{multiplicity})$
  - $\propto (1/\text{passes})$
  - RF costing influenced by total # Watts, CW vs. pulsed

- ERLs are inherently CW devices
  - Avoids transients associated with pulsed power
  - Supports high multiplicity
  - Forces use of lower gradient
    - Changes beam dynamics

- Longitudinal matching (bunch compression & energy recovery processes) differ from conventional linac
  - Typically no harmonic RF (curvature correct with 6-, 8-poles)
  - Think “accelerate then compress”, not “compress, then accelerate”
  - Beam quality preservation issues slightly (subtly) different
System Requirements

*Consider an ERL-driven FEL; it must*

- deliver appropriately configured drive beam of adequate quality to FEL(s):
  - Bunch compression (multistage)
  - Beam quality preservation
  - Multi-FEL distribution
  - Stability, synchronization, jitter mitigation
- recover beam(s) to provide RF power
  - Recombine (merge) multiple output beams for recovery
  - Manage large energy spread/energy compress during energy recovery? – *depends on FEL performance*
FEL Constraints on e⁻ Beam

System dependent, but will involve the usual suspects:

- Angular jitter and position drift
  - Must be smaller than bunch size (~ 40 microns rms)
  - Implies ~10 μrad rms angular jitter, 10 μm position jitter
- Temporal jitter
  - Peak-to-peak temporal jitter plus the seed-pulse full-width must be less than the length of the core of the electron bunch.
- Emittance
  - Must satisfy the emittance requirement
    \[ \varepsilon_N < \frac{\gamma\lambda}{4\pi} \]
- Energy jitter
  - Have to keep energy jitter much less than the Pierce parameter \( \rho \)
- Energy spread
  - Have to keep less than \( \rho \) for fundamental seeding but want even smaller spread for HGHG
FEL Performance

- Estimates (SB; 600 MeV/10 nm HHG seeding w 200 pC beam)
  - $\eta_{\text{FEL}} \sim 1/2\%$
    - High CW power
  - $\Delta E/E_{\text{exhaust}} \sim 3\%$
    - Tens of MeV at $\sim$ GeV energy scale $\Rightarrow$ care needed during energy recovery (especially in multipass system)
Notional Test Implementation
Candidate seed laser and undulator schematic

- The seed laser will reside in a temperature-stabilized hutch on the level above the accelerator vault.
- Beam is routed to HHG source using standard JLab transport components.
Candidate seed laser

- After discussions with a number of laser vendors, the system is currently specified using a KM Labs RedDragon™ system
  - This is somewhat customized (e.g. synchronization) for our applications.
  - Timing jitter is the limit of their measuring capability. Believe it to be lower. (Needs to be measured)
  - Angular stability within the specs of their HHG system.
  - Pulse energy permits direct seeding (with 10-40 nJ pulses) at 108 eV
  - At higher PRFs (10 kHz) we can seed at 36 eV and use HGHG to 108 eV
  - Pre and post pulse contrast ratios high enough to not contaminate the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Pulse energy (mJ)</td>
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<tr>
<td>Pulsed width (fs)</td>
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<td>Rep rate (Hz)</td>
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<td>Amplitude stability (%)</td>
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<tr>
<td>Angular stability (µrad)</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Timing jitter (fs)</td>
<td>&lt;200/fs</td>
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</tbody>
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Seed laser optical transport system requirements are met using existing hardware

- JLab optical transport system had measured performance of 20 μrad pointing stability and beam drift of less than a mm using a collimator (3 reflections) and 5 single turning mirror assemblies.
- We will use 2 mirror assemblies and an active beam position monitoring system to maintain the seed laser’s beam performance.
- High bandwidth of seed laser requires attention to bandwidth and GVD of windows and lenses.
Challenges

• Drive Laser:
  – Pointing stability & position drift; Long term amplitude stability
  – Very high rejection (aka contrast ratio) of unused laser pulses
    • Very low seed rep rate cf. high drive laser fundamental
• e- beam: beam quality preservation issues
• Diagnostics:
  – Time structure may be >10 kHz with single pulses.
    • BPMs must resolve this structure
    • May need to see jitter at this high a frequency
    • Have to compensate RF loading at very high speed.
  – Average current may be fairly low. Bunch length monitor may have to be more sensitive.
• Stability, synchronism, jitter mitigation…
Laser – e beam synchronization

• Generic challenge of synchronizing a 25 fs seed laser pulse with a 100 fs e beam

• ERL (recirculating linac) geometry provides time-of-flight advantage
  – Allows feed-back over much shorter distance than beam path

  • Circulation time \( \sim 0.4 \text{ \mu sec} \)
Synchronization
FEL-Seeded
ERL-Driven XFEL

Two bunch trains
UV seed, XFEL drive
RF separation in 1st pass
UV bypass $\lambda_{RF}/2$ longer
(recovers bunch train)

Issues:
SYNCHRONISM
UV seed pulse energy,
up-conversion
GERBAL

- Machine configuration:

- Transverse optics
Conclusions

• Due to the low rep rate relative to the linac RF frequency, seeded FELs in an ERL-based accelerator impose different requirements on their hardware relative to an oscillator-based FEL
  – Requires a higher contrast ratio (achievable) on drive laser pulses in order to minimize the effects of ghost pulses.
• Requires a high level of synchronism between photon and electron pulses
• Low beam loading make ERL unnecessary today – but provide opportunities for tomorrow:
  – Service to multiple FELs of multiple architectures
  – Leverage evolution in seed lasers/seeding schemes
  – FEL-seeded FELs?
Perspective

- Rings – very advanced systems – equivalent to nanotechnology or rocket science.

- "conventional" FELs – perhaps not as advanced, but still very sophisticated – like cathedrals or bridges.

- ERLs – in infancy (or "terrible twos"…) – stone knives and animal skins.

But at least ERLs are so easy!