On the Design Implications of Incorporating an FEL in an ERL


August 24, 2006

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Introduction

• A number of ERLs are being designed and constructed around the world

• Including FELs place additional stringent requirements on the technical specifications of the accelerator systems

• Many of the requirements are crucial and difficult to achieve. A non-comprehensive list:
  • Longitudinal phase space manipulation
  • Energy stability
  • Phase stability
  • Transverse and longitudinal acceptance
  • Magnetic field quality tolerance
  • Wakefields and resistive wall instability management

• This talk will discuss the limits on these parameters and how they arise
Longitudinal Matching Example

Accelerate off crest with long bunch
Compress before wiggler
Decelerate off negative crest for energy recovery and energy spread compression
Offset phase on return sets limit on energy spread

- FEL Interaction: beam central energy drops, beam energy spread grows
- Recirculator energy must be matched to beam central energy to maximize acceptance
- Beam rotated, curved, torqued to match shape of RF waveform
- Maximum energy can’t exceed peak deceleration available from linac!

\[
\frac{(\Delta E/E)_{\text{FEL}}}{2} < E_{\text{linac}} \cos \phi_0
\]
Current Loading

The $M_{56}$ between the end of our FEL and the linac is $\sim 0.2$ m
Lasing at 2% efficiency the phase shift is 7.2 degrees of rf at 1500MHz

10 MV/m, +10° accel/decel
Effective 10 mA current sum = 0

Same but return delayed 7.2°
Effective current sum = 1.2 mA @ 284°

The rf control module must handle this huge shift when the FEL turns on
Rf phase vector diagrams

The M56 between the end of our FEL and the linac is ~0.2m.
Lasing at 2% efficiency the phase shift is 7.2 degrees of rf at 1500MHz.

10 MV/m, +10° accel/decel
Generator power phasor

Same but return delayed-7.2°
Instantaneous power phasor

Same but return delayed-7.2°
tuner minimizes power phasor

High $Q_L$ only makes this shift worse!

Klystron Power
“Cavity” Power
“Beam” Power

Yes, I know power isn’t a vector; length shown is $E$. 
RF Power as a function of current

RF power as a function of beam current cavity FEL3-4, first pass -10d second pass +160d off crest, CW, tuners on

Beam Current (mA) vs RF Power (kW)

- Predicted After Tuner Nulls Out Imag Part
- Predicted With Fixed Tuner Position
- Actual Values Taken Every Two Seconds During the Run
Timing jitter requirements

Optical cavity must have its round trip travel time precisely matched to the arrival time of the electron bunches.
To keep the peak to peak fluctuations smaller than 10% it is necessary to keep the cavity length stable to less than $0.05GN\lambda$.

Example: JLab IR Upgrade

For $G$ of 0.5, $N$ of 32, and $\lambda$ at 1.5 µm. One must keep the cavity length constant to <1.2 µm peak to peak. Arrival time must be kept constant to the same precision:

\[
\frac{\delta\omega}{\omega} < \frac{\delta L}{L} < \frac{1.2 \times 10^{-6}}{32} = 3.8 \times 10^{-8}
\]

From the frequency modulation constraint you get a timing jitter constraint of \( \delta\tau < 6\times10^{-9}/f_m \).
If you want to bunch a beam for high peak current you are limited by the longitudinal emittance and any non-linearities in the system.

If you aren't careful the non-linearities can dominate the result.
Component Quality

- This will make or break a machine!
- Magnetic field errors & ripple cause timing errors, energy spread, etc…
- **Power supply stability, resolution, etc** – couples to
  - timing stability at FEL (in compaction managed transport systems)
  - magnet reproducibility: hysteresis program!
- **Magnetic field quality**
  - Distorts not only transverse phase space, but also longitudinal
Field Quality Limitations to ERL Performance

- \( \Delta B \Rightarrow \delta x' = \Delta B_l/B\rho \sim \Delta B_l/(33.3564 \text{ kg-m/GeV} \ast E_{\text{linac}}) \)

- \( \delta l \Rightarrow \Delta E_{\text{dump}} = \sin \phi_0 (2\pi M_{52}(\Delta B_l/33.3564 \text{ kg-m})/\lambda_{RF}) \text{ (GeV)} \)

- “Error field integral” \( \Delta B_l \) is independent of linac length/energy gain
  - tolerable relative field error falls as energy (required field) goes up

- Numbers for 160 MeV Upgrade:
  - \( \Delta E_{\text{dump}} \sim 3400 \text{ MeV} \ast (\Delta B/B) \)
  - \( \Delta E_{\text{dump}} \sim 0.16 \text{ keV/g-cm} \ast (\Delta B_l) \)
If you do it right then linac produces stable ultrashort pulses

We now regularly achieve 300 fs FWHM electron pulses
And so does the FEL: FROG Analysis of JLAB FEL Pulses

- Laser: CW 1 kW
- Wavelength: 1.6 μm
- FWHM 215 fs

SHG FROG Traces

FROG error is 0.0015

 Courtesy S. Zhang
Wakefields

Ordinary vacuum crosses can turn into resonant chambers!
Worse for ERL than SR because of short pulses

55°C temperature on window with only 4.6 mA
Estimate 20V/pC impedance at resonant frequency of 1450 MHz.
OOPS!
Resistive wall heating in wiggler (11 mm chamber)

This can lead to enormous power deposition in the walls; the situation is much worse for ERLs than storage rings because of the shorter pulses!

42°C on the edge, 100°C in the middle with only 4.6 mA
OOPS!
Summary

ERLs offer exciting possibilities for extending light source performance however these opportunities do not come without major challenges which push the limits of many technologies.

The incorporation of FELs in ERLs adds to the list of issues which must be dealt with and tightens many specifications.

The issues become more difficult with higher charge, longer systems, shorter pulses, and higher average currents but strategies exist to attack these problems.
The work discussed was performed by the FEL Team:

With the help of lots of others at JLab

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, and by DOE Contract DE-AC05-84ER40150.