RF Control Requirements in Energy Recovery Linacs

Lia Merminga

Jefferson Lab
Newport News, VA

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Outline

- Energy Recovery Linacs (ERLs)
  - ERL-based FELs / The JLab IR FEL and FEL Upgrade
  - ERL-based Synchrotron Light Sources / The Cornell ERL (Proposed)
  - ERL-based Colliders: eRHIC, EIC (Conceptual Designs)
- Efficiency of ERLs
  - Power Requirements
- Amplitude and Phase Stability Requirements
- RF Stability
- Conclusions
Energy Recovery Linacs

- Energy recovery is the process by which the energy invested in accelerating a beam is returned to the rf cavities by decelerating the same beam.

- There have been several energy recovery experiments to date, the first one at the Stanford SCA/FEL.

- Same-cell energy recovery with cw beam current up to 5 mA and energy up to 50 MeV has been demonstrated at the Jefferson Lab IR FEL. Energy recovery is used routinely for the operation of the FEL as a user facility.
The JLab 1.7 kW IRFEL and Energy Recovery Demonstration

Energy Recovery Works

Gradient modulator drive signal in a linac cavity measured without energy recovery (signal level around 2 V) and with energy recovery (signal level around 0).

![Graph showing the comparison of gradient modulator drive signal with and without energy recovery.](image-url)
Energy Recovery Works (cont’d)

With energy recovery the required linac rf power is ~ 16 kW, nearly independent of beam current. It rises to ~ 36 kW with no recovery at 1.1 mA.
The JLab 10 kW FEL Upgrade
Cornell ERL Prototype

- Dipole
- Quadrupole
- Kick
- Vacuum Valves

to Dump
Linac–Ring Collider: Schematic Layout
Benefits of Energy Recovery

- Required rf power becomes nearly independent of beam current.

- Increases overall system efficiency.

- Reduces electron beam power to be disposed of at beam dumps (by ratio of $E_{\text{fin}}/E_{\text{inj}}$).

- If the beam is dumped below the neutron production threshold, then the induced radioactivity (shielding problem) will be reduced.
RF to Beam Multiplication Factor for an ideal ERL

\[ E_{\text{acc}} = 20\text{MV/m} \]
\[ Q_L = 2 \times 10^7 \]
\[ E_{\text{inj}} = 10\text{MeV} \]
\[ E_f = 7\text{GeV} \]

\[ K \equiv \frac{P_{\text{beam}}}{P_{\text{RF}}} \approx \frac{JE_f}{(J - 1)E_{\text{inj}} + E_f} \]

\[ J = \frac{\bar{I}(r/Q)Q_L}{E_{\text{acc}}} \]

Krafft, Merminga, 2000
Multiplication Factor vs. Loaded Q

\[ E_{acc} = 20 \text{ MV/m} \]
\[ E_{inj} = 10 \text{ MeV} \]
\[ E_f = 7 \text{ GeV} \]
Can we further improve the ERL efficiency?

- In practice, for an ideal ERL ($I_{\text{tot}}=0, \Delta \psi=180^\circ$):
  
  $$\beta_{\text{opt}} = \sqrt{1 + \left( \frac{2Q_0 \delta f_m}{f_0} \right)^2}$$

  $\delta f_m$ is the maximum microphonic noise to be controlled.

- In order to further improve the ERL efficiency, the following questions are of primary importance:
  
  - What is the maximum achievable $Q_L$?
  - Microphonics control?
  - Lorentz force detuning?
Real ERLs

- Phases may not differ by precisely 180°
  - Typical expected path length control adjustment leads to ~ 0.5° deviation from 180°
  - In an FEL, if machine is setup so that beam current vectors cancel with FEL on, then with FEL off, there can be up to 5° deviation from perfect cancellation

- Beam loss may occur, resulting in beam vectors of unequal magnitude
- Beam current fluctuations

⇒ All of the above give rise to a net beam loading vector, typically of reactive nature in the case of phase errors
⇒ Increase of rf power requirements and reduction of κ
Energy Recovery Phasor Diagram
Power Requirements

- Is there a better way to deal with sudden increase in power demands (predicted or unpredicted)?
- Can the requirements on tuners be met?
- Quality of regulation as function of beam current?
RF Control (Injector)
Amplitude and Phase Stability Requirements

- End users impose certain phase and amplitude stability requirements in order for the energy spread and timing jitter specifications at the interaction point (FEL, undulator, interaction region) to be met.

- These requirements determine characteristics of the LLRF control system, including gain and bandwidth of the feedback loops.

- In ERLs, additional constraints on the LLRF system design may be imposed due to possible longitudinal instabilities.
RF Instabilities

- Instabilities can arise from fluctuations of cavity fields.
- Two effects may trigger unstable behavior:
  - Beam loss which may originate from energy offset which shifts the beam centroid and leads to scraping on apertures.
  - Phase shift which may originate from energy offset coupled to $M_{56}$ in the arc
- Instabilities predicted and observed at LANL, a potential limitation on high power recirculating, energy recovering linacs.

\[ \Delta l = M_{56} \frac{\Delta E}{E} \]

$M_{56}$ is the momentum compaction factor and is defined by:
RF STABILITY FLOW CHART

- Energy
- Aperture
- Beam loss
- $\Delta E$
- $M_{56}$
- Freq. shift
- $\Delta G$
- $\Delta P_{\text{light}}$
- Phase shift
- $\Delta V_b$
- Feedback
- $\Delta V_c$
RF Stability Model

- Developed model of the system that includes beam-cavity interaction, low level rf feedback and the FEL; it was solved analytically and numerically.

- Model predicts instability exists in the IRFEL, however is controlled by LLRF feedback.

- When FEL is off, experimental data from the IRFEL are quantitatively consistent with the model. With FEL on, model reproduces data qualitatively.
FEL/RF INTERACTION: EXPERIMENT VS MODEL

![Graphs showing phase error and relative FEL power modulation amplitude as functions of modulation frequency.](image-url)
Conclusions

- Energy recovery linacs are very efficient devices for certain applications

- We have asked two questions:
  - Can we increase the efficiency of ERLs by optimizing the rf control system design?
  - Can we ensure stability at high average currents with better rf control system design?