RF Issues in Energy Recovery Linacs

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Outline

- Energy Recovery Linacs (ERLs)
  - Examples
  - Basic features
- Efficiency of ERLs
  - Power Requirements
- RF Stability
- Higher-Order Modes Issues
- 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
  • Stanford SCA/FEL
  • Los Alamos FEL
  • CEBAF front end

• 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


[Diagram of the JLab 1.7 kW IRFEL and Energy Recovery system]
Demonstration of Energy Recovery

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).
Demonstration of Energy Recovery

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.

![RF Power vs Cavity Number Graph](image-url)
Linac–Ring Collider: Schematic Layout

Polarized Electron Source

Energy Recovery Electron Linac

Proton Ring

Electron Beam Dump
Features of Energy Recovery

- With the exception of the injector, the required rf power is nearly independent of beam current.
  - Increased overall system efficiency.

- The electron beam power to be disposed of at beam dumps is reduced by ratio of $E_{\text{max}}/E_{\text{inj}}$.
  - Thermal design of beam dumps is simplified
  - 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

\[ J = \frac{P_b}{P_g} \]

Power absorbed by accelerated beam
Generator power needed to create and control rf fields

\[ J = \frac{VI}{v_c^2} = \frac{2I}{E} \left( \frac{R}{lQ} \right) Q_L \]

\[ \kappa = \frac{\text{Accelerated beam power}}{\text{Installed rf power}} \]

\[ \kappa = \frac{JE_f}{(J-1)E_{inj} + E_f} \]
RF to Beam Multiplication Factor for an ideal ERL

\[ E_{\text{acc}} = 20 \text{ MV} / m \]
\[ R/lQ = 1000 \Omega / m \]
\[ E_{\text{inj}} = 10 \text{ MeV} \]
\[ E_f = 7 \text{ GeV} \]

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**Graph**

- **Axes:**
  - **Horizontal (x-axis):** Beam Current (mA)
  - **Vertical (y-axis):** RF to Beam Multiplication Factor

**Legend:**
- Red line: \( Q_l = 10^8 \)
- Blue line: \( Q_l = 2 \times 10^7 \)
RF to Beam Multiplication Factor for an ideal ERL

- The efficiency of an ERL (as measured by the rf to beam multiplication factor) increases with current
  - Asymptotic value is $E_{\text{max}}/E_{\text{inj}}$

- The efficiency increases with the loaded Q of the energy-recovering cavities
Q\textsubscript{ext} Optimization

- Condition for optimum coupling:
  \[ \beta_{opt} = \sqrt{(b+1)^2 + \left(2Q_0 \frac{\delta f_d}{f_0}\right)^2} \]

  and
  \[ P_{g, opt} = \frac{V_c^2}{2(r/Q)Q_0} \left[ |b+1| + \sqrt{(b+1)^2 + \left(2Q_0 \frac{\delta f_d}{f_0}\right)^2} \right] \]

- In the absence of beam (b=0):
  \[ \beta_{opt} = \sqrt{1 + \left(2Q_0 \frac{\delta f_d}{f_0}\right)^2} \]

  and
  \[ P_{g, opt} = \frac{V_c^2}{2(r/Q)Q_0} \left[ 1 + \sqrt{1 + \left(2Q_0 \frac{\delta f_d}{f_0}\right)^2} \right] \cdot 2\pi U \delta f_d \]
Generator Power vs. Loaded Q

7-cell, 1500 MHz

P (kW)

Qext (10^6)

- 20.0 MV/m, 0 uA, 50 Hz 0 deg
- 20.0 MV/m, 0 uA, 38 Hz 0 deg
- 20.0 MV/m, 0 uA, 25 Hz 0 deg
- 20.0 MV/m, 0 uA, 13 Hz 0 deg
- 20.0 MV/m, 0 uA, 0 Hz 0 deg

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Q_{ext} for ERL Injector and Linac Cavities

- **ERL Injector (2-cell) cavities:**
  - \( f_0 = 1300 \text{ MHz}, \ Q_0 = 5 \times 10^9, \ V_c = 1 \text{ MV per cavity}, \ L_{cav} = 23 \text{ cm} \)
  - For \( I_0 = 100 \text{ mA} \) \( \Rightarrow \) Optimum \( Q_L = 4.6 \times 10^4 \) \( \Rightarrow \) \( P_g = 100 \text{ kW per cavity} \)
  - Note: \( I_0 V_a = 100 \text{ kW} \) \( \Rightarrow \) optimization is entirely dominated by beam loading

- **ERL linac (9-cell) cavities:**
  - \( f_0 = 1300 \text{ MHz}, \ Q_0 = 1 \times 10^{10}, \ V_c = 20 \text{ MV/m}, \ L_{cav} = 1.04 \text{ m} \)
  - \( R/Q = 1036 \text{ ohms}, \ \delta f_m = 25 \text{ Hz} \)
  - Resultant beam current, \( I_{tot} = 0 \text{ mA} \) (energy recovery)
  - \( \Rightarrow \) Optimum \( Q_L = 2.6 \times 10^7 \) \( \Rightarrow \) \( P_g = 8 \text{ kW per cavity with } \delta f_m = 25 \text{ Hz} \)
  - Note: optimization is entirely dominated by amplitude of microphonic noise
Increasing the Efficiency of ERLs

What is the maximum achievable loaded Q for energy-recovering cavities?

- Microphonics control
- Lorentz force detuning
- Non-ideal energy recovery
Self-Excited Loop-Principle of Stabilization

Controlling the external phase shift $\theta_l$ can compensate for the fluctuations in the cavity frequency $\omega_c$ so the loop is phase locked to an external frequency reference $\omega_r$.

$$\omega = \omega_c + \frac{\omega_c}{2Q} \tan \theta_l$$

Instead of introducing an additional external controllable phase shifter, this is usually done by adding a signal in quadrature

$\Rightarrow$ The cavity field amplitude is unaffected by the phase stabilization even in the absence of amplitude feedback.
Self-Excited Loop – Block Diagram
Non-Ideal Energy Recovery

- Ideal energy recovery assumes perfect cancellation of 2 large and opposite vectors
  - Accelerated and decelerated beams are equal in magnitude and 180° out of phase at the fundamental frequency
- In practice there will be a residual net current:
  - Phases may not differ by precisely 180°
  - Typical expected path length control adjustment leads to ~ 0.5° deviation from 180°
  - Beam loss may occur, resulting in beam vectors of unequal magnitude
  - High-frequency beam current fluctuations

⇒ All of the above give rise to a net beam loading vector, of random amplitude and phase, but that will typically be reactive
⇒ Increase of rf power requirements and reduction of κ
Energy Recovery Phasor Diagram
Sensitivity Analysis: Beam Loss

![Graph showing the sensitivity analysis of beam loss vs generator power.]
Sensitivity Analysis: Phase Errors

Optimum tuning condition is assumed
Amplitude and Phase Stability Requirements

- Specifications set by the users on energy spread and timing jitter will impose requirements on the phase and amplitude stability in the cavities.

- These requirements will determine the 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.

$M_{56}$ is the momentum compaction factor and is defined by:

$$\Delta l = M_{56} \frac{\Delta E}{E}$$
RF Stability Flow Chart

ΔE

Energy
Aperture

Beam loss

ΔV_b

Phase shift

M_{56}

ΔV_c

Feedback

X
RF Stability Studies

- Model has been developed (Lia Merminga) in support of the Jlab FEL program. It includes:
  - beam-cavity interaction,
  - low level rf feedback
  - FEL interaction

- Solved analytically and numerically

- Model predicts instabilities that agree with experimental measurements performed on JLab IRFEL
  - Agreement is quantitative with FEL off
  - Agreement is qualitative with FEL on

- Instabilities can be controlled by LLRF feedback
  - Further analysis and modeling is needed to understand the rf stability issues of ERLs with much higher current (Control of random reactive loading currents in superconducting cavities)
Higher Order Modes

• Even in the case of perfect energy recovery cancellation of accelerated and decelerated beam occurs only at the fundamental mode frequency

• Coupling to other monopole modes
  • HOM power dissipation

• Coupling to dipole modes
  • Beam breakup instabilities
HOM Power Dissipation

- Accelerated and decelerated beams will couple to the (non fundamental) monopole modes and will deposit energy in those modes.

- Power dissipated depends on product of bunch charge and average current
  \[ P_{\text{diss}} = 2kQ \langle I \rangle \]

- For typical TESLA-type cavities \( k \sim 8.5 \text{ V/pC} \) for \( \sigma_z \sim 1 \text{ mm} \)
  \[ \langle I \rangle \sim 250 \text{ mA}, \ Q \sim 2 \text{ nC} \]
  \[ P_{\text{diss}} \sim 8 \text{ kW/cavity} \]

- Need a better understanding of where that power goes
  Only a small fraction ends up on the cavity walls

- Need engineering development of HOM absorbers
Beam Breakup Instabilities

- Coupling of accelerated and decelerated beams to dipole modes

- Single bunch, single pass effects: limit the bunch charge
  - Energy spread induced by variation of longitudinal wake field across bunch
  - Emittance growth induced by single-bunch transverse BBU
(Multi-Bunch) Beam Breakup Instabilities

- Multi-pass, multi-bunch effects: limit the average current

- Recirculating beam through a cavity can lead to transverse instabilities
  - Transverse displacement on successive recirculations can excite HOMs that further deflect initial beam
  - Feedback loop between beam and cavities
  - Threshold current above which the system becomes unstable
  - Because of their high Q, superconducting systems can be more sensitive to this type of instability

- TDBBU: 2d beam breakup code used for simulation (Krafft, Bisognano, Yunn)
  - Being benchmarked at the JLab FEL
  - Predicts threshold current of ~ 250 mA, and rise time of ~ 2 msec.
Conclusions

• Energy recovery superconducting linacs are very efficient devices for certain applications
  • They can approach the efficiency of storage rings while preserving the beam properties of linacs
• Concept has been fully demonstrated and is used routinely in a user facility
• Studies have uncovered no fundamental show stoppers
• The ultimate limits of the energy-recovering concept have not been fully determined
  • Highest $Q_1$ for the cavities while maintaining phase and amplitude stability requirements
  • Highest current that can be accelerated/decelerated
    • Preservation of rf stability
    • Avoidance BBU instabilities
    • Extraction of HOM power
    • Control of beam loss