AN ENERGY-RECOVERY ELECTRON LINAC-ON-PROTON RING COLLIDER

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Newport News, VA

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OUTLINE

- Energy Recovery Linacs
  - Experiments to date
  - Energy Recovery Works
  - Benefits of Energy Recovery
- An electron linac-on-proton ring collider reasoning & point design
  - No proton cooling
  - Proton cooling
  - Dependence on energies
- Accelerator Physics of Proton Ring
  - Intrabeam scattering
  - Collective Effects
OUTLINE (cont’d)

- Accelerator Physics of Energy Recovery Linacs (ERLs)
  - Source
  - Accelerator Transport
  - Coherent Synchrotron Radiation
  - RF Stability
  - Higher Order Modes and Beam Breakup
- Linac – Ring Instabilities
- Conclusions
ENERGY RECOVERY

Definition
Process by which energy is transferred to the rf cavities by the decelerating beam.

Major Energy Recovery Experiments to date
- Stanford SCA/FEL
- Los Alamos FEL
- CEBAF Injector
- Jefferson Lab 1.7 kW FEL
THE SCA/FEL ENERGY RECOVERY EXPERIMENT

THE CEBAF INJECTOR ENERGY RECOVERY EXPERIMENT

Gradient modulator drive signals in 4 linac cavities measured without energy recovery (signal level around 2 V) and with energy recovery (signal level around 0).
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).
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.
With energy recovery the required rf power is 25 kW independently of beam current. With no recovery the required rf power at 4 mA would have been 160 kW.
**BENEFITS OF ENERGY RECOVERY**

AC Power Draw in IR Demo: 1.7 kW FEL output
Beam 5 mA, 48 MeV

<table>
<thead>
<tr>
<th>Component</th>
<th>With Energy Recovery (measured)</th>
<th>Without Energy Recovery (estimates)</th>
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</thead>
<tbody>
<tr>
<td>Injector RF</td>
<td>220 kW</td>
<td>220 kW</td>
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<tr>
<td>Linac RF</td>
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</tr>
<tr>
<td>He Refrigerator</td>
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<td>70 kW</td>
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<tr>
<td>(Estimated)</td>
<td></td>
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<tr>
<td>Magnets, Computers, etc.</td>
<td>43 kW</td>
<td>23 kW</td>
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<tr>
<td>Total</td>
<td>508 kW</td>
<td>1013 kW</td>
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</tbody>
</table>

**BENEFITS OF ENERGY RECOVERY**

**AC Power Draw in IR Upgrade: 10 kW FEL output**
Bean 10 mA, 160 MeV

<table>
<thead>
<tr>
<th>Component</th>
<th>With Energy Recovery (estimates)</th>
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<tr>
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<tr>
<td><strong>Total</strong></td>
<td><strong>1075 kW</strong></td>
<td><strong>4690 kW</strong></td>
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RF TO BEAM EFFICIENCY

\[
\eta_b^{RF} = \frac{P_{beam}}{P_{RF}} \frac{JE_f}{(J - 1)E_{inj} + E_f}
\]

\[
J = \frac{4I(r/Q)Q_L}{G_a}
\]

Diagram shows a graph with beam current in mA on the x-axis and RF to beam efficiency on the y-axis. The graph is labeled "fort.20" and shows a curve that increases as the beam current increases.
SUMMARY OF BENEFITS

- 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 $E_{\text{fin}}/E_{\text{inj}}$).

- More importantly, reduces induced radioactivity (shielding problem) if beam is dumped below the neutron production threshold.
Input parameters: \( E_e = 3 \text{ GeV} \) and \( E_p = 15 \text{ GeV} \)

Reasoning:
- Set electron beam size at IP based on projected source performance
- Set proton beam parameters at Laslett tuneshift limit
- Determine number of electrons per bunch
- Determine collision frequency
ELECTRON BEAM PARAMETERS AT IP

• Assume $\varepsilon_n \sim 60 \ \mu m$ at $Q \sim 1 \ nC$
  (Emittance dilution in linac will be addressed below)

• At $E_e = 3 \ GeV$, $\varepsilon_e^* = 10 \ nm$

• For $\beta^* = 12 \ cm$, $\sigma_e^* = 35 \ \mu m$
  (Round beams are assumed for electrons and protons)
PROTON BEAM PARAMETERS

- For $\sigma_z \approx \beta_p^*$ Laslett tuneshift sets a limit on $N_p / \sigma_p^{*2}$

\[
\Delta \nu_L = \frac{N_p r_p}{4 \pi \gamma_p^3 \varepsilon_x^*} \frac{C}{\sqrt{2\pi} \sigma_z}
\]

- Without proton cooling we assume $\Delta \nu_L \leq 0.004$

- For $\varepsilon_{n,p} = 3 \, \mu\text{m} (\text{LHC, RHIC}), \ \beta^* = 6 \, \text{cm} \Rightarrow \sigma_p^* = 107 \, \mu\text{m}$

and

$N_p = 3 \times 10^{10}$

at the Laslett tuneshift limit.
NUMBER OF ELECTRONS PER BUNCH

$N_e$ can be limited by:

- Beam-beam tuneshift of proton beam

$$\xi_p = \frac{N_e r_p \beta_p^*}{4 \pi \gamma_p \sigma_e^*}$$

For $\xi_{pr} = 0.004$,  $N_e = 1.1 \times 10^{10}$

- Emittance growth due to single-bunch transverse BBU in the linac

$$\eta = \frac{L v_e N_e W}{\kappa_0 \left( \gamma_f - \gamma_0 \right) \ln \frac{\gamma_f}{\gamma_0}}$$

For $\sigma_z = 1$ mm, $\lambda_p = \frac{2\pi}{k_0}$,  $N_e = 1.5 \times 10^{11}$

(BNS damping could be used if this becomes the limit.)
Maximize $f_c$ subject to constraints:
- Parasitic collisions
- User requirements
- Electron cloud effect

Assume bunch separation of 6.66 nsec or

$$f_c = 150 \text{ MHz}$$
LUMINOSITY W/OUT PROTON COOLING

\[ L = \frac{N_e N_p f_c}{2\pi \left[ \sigma_e^{*2} + \sigma_p^{*2} \right]} \]

\[ N_e = 1.1 \times 10^{10} \]
\[ N_p = 3.0 \times 10^{10} \]
\[ f_c = 150 \text{ MHz} \]
\[ \sigma_e^{*} = 35 \text{ µm} \]
\[ \sigma_p^{*} = 107 \text{ µm} \]

\[ L = 6.2 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1} \]
# EPIC PARAMETER TABLE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
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<td>$\sigma_e^*$</td>
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<td>0.0068*</td>
<td>0.004</td>
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<td>$\nu\nu L$</td>
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<td>0.05*</td>
<td>0.004</td>
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<td>$6.2 \times 10^{31}$</td>
<td>$5.7 \times 10^{32}$</td>
<td>$6.2 \times 10^{32}$</td>
<td>$2.1 \times 10^{33}$</td>
</tr>
</tbody>
</table>
A POINT DESIGN WITH PROTON COOLING

- Electron beam parameters remain the same
- Laslett and beam-beam tuneshifts allowed to reach

\[ \Delta \nu_L \leq 0.05 \]

\[ \zeta_p \leq 0.05 \]

- Laslett tuneshift sets ratio \( N_p / \sigma_p^2 \)
- Optimization now as follows:
  - Determine limit on \( N_p \)
  - Determine minimum \( \sigma^* \) at the Laslett tuneshift
NUMBER OF PROTONS PER BUNCH

$N_p$ can be limited by:

- Emittance growth of electrons due to single round-beam collision
- Proton ring instabilities
EMITTANCE GROWTH DUE TO A SINGLE COLLISION

- A single collision disrupts the electron beam and causes emittance growth.
- Electron beam with degraded phase space has to be recirculated and energy recovered.
- Adiabatic antidamping can result in scraping and beam loss in the cryomodules.
- Therefore, amount of tolerable beam loss at the linac exit imposes a limit on tolerable emittance growth due to collision. This in turn imposes a limit on $N_p$. 
EMITTANCE GROWTH (cont’d)

- Assume maximum tolerable beam loss:
  \[4 \times 10^{-6} \quad (1 \, \mu\text{A}/250 \, \text{mA})\]

- Assume gaussian distribution, aperture = 7 cm, average \(\beta\)-function in linac \(\sim 50\) m, then
  \[\varepsilon_n < 800 \, \mu\text{m}\]

- In the small disruption limit:
  \[\varepsilon_n^2 = \varepsilon_{0,n}^2 + (0.194 \, r_e \, N_p)^2\]

- For \(\varepsilon_{0,n} = 60 \, \mu\text{m}, \varepsilon_n = 800 \, \mu\text{m},\)
  \[N_p \leq 1.5 \times 10^{12} \, \text{ppb}\]
Determine proton beam parameters (cont’d)

- We assume
  \[ N_p \sim 1 \times 10^{11} \]
  same as LHC, RHIC.
  (We will check collective effects later.)

- At the Laslett tuneshift
  \[ \sigma_p^* = 58 \, \mu m \]

- For \( \beta^* = 0.1 \, m \),
  \[ \epsilon_p^* = 33.6 \, \text{nm} \text{ or } \epsilon_n = 0.54 \, \mu m \]

At \( N_e \sim 1.1 \times 10^{10} \), \( \xi_{pr} = 0.0068 \)
LUMINOSITY WITH PROTON COOLING

\[ L = \frac{N_e N_p f_c}{2\pi[\sigma_e^* + \sigma_p^*]} \]

\( N_e = 1.1 \times 10^{10} \)
\( N_p = 1.0 \times 10^{11} \)
\( f_c = 150 \text{ MHz} \)
\( \sigma_e^* = 35 \text{ µm} \)
\( \sigma_p^* = 58 \text{ µm} \)

\[ L = 5.7 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1} \]
## DEPENDENCE ON ENERGIES

Examine $E_e = 5\text{ GeV}$ and $E_p = 50\text{ GeV}$

<table>
<thead>
<tr>
<th>W/out cooling</th>
<th>With cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_e = 1.1 \times 10^{10}$</td>
<td>$N_e = 1.1 \times 10^{10}$</td>
</tr>
<tr>
<td>$N_p = 1.0 \times 10^{11}$</td>
<td>$N_p = 1.0 \times 10^{11}$</td>
</tr>
<tr>
<td>$f_c = 150\text{ MHz}$</td>
<td>$f_c = 150\text{ MHz}$</td>
</tr>
<tr>
<td>$\sigma_{e^*} = 25\text{ \mu m}$</td>
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</tr>
<tr>
<td>$\sigma_{p^*} = 60\text{ \mu m}$</td>
<td>$\sigma_{p^*} = 25\text{ \mu m}$</td>
</tr>
</tbody>
</table>

$L = 6.2 \times 10^{32}\text{ cm}^{-2}\text{ sec}^{-1}$  
$L = 2.1 \times 10^{33}\text{ cm}^{-2}\text{ sec}^{-1}$
ACCELERATOR PHYSICS ISSUES OF PROTONS

Intrabeam Scattering: Transverse

\[ \tau_{tr} = \frac{2\pi}{\Lambda} \gamma_p^3 \beta_p \frac{R^2}{r_p^2} \left( \frac{\varepsilon_x}{\beta_{av}} \right)^{5/2} \frac{\sigma_z}{c} \frac{1}{N_p} \]

At 15 GeV

w/out cooling: \( \tau_{tr} = 33043 \) sec

with cooling: \( \tau_{tr} = 79 \) sec

At 50 GeV

w/out cooling: \( \tau_{tr} = 5.9 \times 10^5 \) sec

with cooling: \( \tau_{tr} = 1162 \) sec
ACCELERATOR PHYSICS OF PROTONS (cont’d)

Intrabeam Scattering: Longitudinal

\[ \tau_{\text{long}} = \frac{8\gamma_p^3 \sigma_z \varepsilon_x^{3/2} (\sigma_E / E)^2}{cr_p^2 N_p \Lambda} \sqrt{\frac{C}{2\pi\nu_x}} \]

At 15 GeV

w/out cooling: \( \tau_{tr} = 1.25 \times 10^3 \) sec @ \( \sigma_E / E = 1.5 \times 10^{-3} \)

with cooling: \( \tau_{tr} = 30 \) sec @ \( \sigma_E / E = 1.5 \times 10^{-3} \)

At 50 GeV

w/out cooling: \( \tau_{tr} = 1.1 \times 10^4 \) sec @ \( \sigma_E / E = 3 \times 10^{-3} \)

with cooling: \( \tau_{tr} = 900 \) sec @ \( \sigma_E / E = 3 \times 10^{-3} \)
Collective Effects

• Longitudinal mode coupling or microwave instability

$$\left| \frac{Z \perp}{n} \right| = \sqrt{\frac{\pi}{2}} \frac{Z_0 \alpha \gamma \sigma^2 \sigma_z}{N_p r_p}$$

For $$\left| \frac{Z \perp}{n} \right| \sim 0.25 \, \Omega$$ (LHC, Tevatron)

$$N_p < 6 \times 10^{12}$$

• Transverse mode coupling instability (for $$\sigma_z > b$$)

$$\left| Z \perp \right| = Z_0 \frac{\pi \gamma \omega_s \sigma_z}{3 N_p r_p \beta_\text{av} \omega_0}$$

For $$\left| Z_{\text{tr}} \right| \sim 5 \times 10^4 \, \Omega$$ (scaled from LHC)

$$N_p < 1.8 \times 10^{12}$$
ACCELERATOR PHYSICS OF ERL

- Source
- Accelerator Transport
  - Longitudinal & Transverse Matching
  - Beam Loss
- Coherent Synchrotron Radiation
- RF Control & Stability
- Higher Order Modes (HOM) & Beam Breakup (BBU)
  - HOM Power Dissipation
  - Multipass-Multibunch BBU
POLARIZED ELECTRON LINAC SOURCES

- For a polarization of 80% extensive laser R&D is necessary
- For a polarization of 30% commercial lasers are available
- To achieve sufficient lifetime vacuum is of paramount importance
- Photo cathode has to be cooled
- Bunch charge of 17 nC can be delivered from a highly doped GaAs photo cathode
- Acceleration voltage should at least be 200 kV
- Beam emittance is not an issue; 1.4 mm-mrad thermal emittance expected at 17 nC, 170 mA
- Required emittance is ~60 mm-mrad at 1.7nC, 264 mA

Hartmann, Sinclair et al., eRHIC Workshop, April’99
ACCELERATOR TRANSPORT

- Longitudinal Matching
- Transverse Matching
- Beam Loss
LONGITUDINAL MATCHING

Requirements

- high peak current (short bunch) at FEL
- small energy spread at dump

\[ \sigma_z \sim 0.4 \text{ ps} \quad \Delta E \sim 2 \text{ MeV} \]
\[ \sigma_z \sim 0.4 \text{ ps} \quad \sigma_E \sim 60 \text{ keV} \]
\[ \sigma_z \sim 1.2 \text{ ps} \quad \sigma_E \sim 60 \text{ keV} \]
\[ \sigma_z \sim 1.2 \text{ ps} \quad \sigma_E \sim 16 \text{ keV} \]

\[ \Delta z \sim 30 \text{ ps} \quad \Delta E \sim 100 \text{ keV} \]
\[ \Delta z \sim 30 \text{ ps} \quad \Delta E \sim 2 \text{ MeV} \]
TRANSVERSE MATCHING

- Provide appropriate transverse phase space matching into the “interaction region”
  - For IRFEL, good overlap between electron beam and optical mode
  - For EPIC, good overlap to maximize luminosity
- Transport beam with likely degraded phase space around the recirculator
  - For IRFEL, transport and energy recover large momentum spread
  - For EPIC, transport and energy recover disrupted electron beam
- Deal with adiabatic antidamping in the linac
TRANSVERSE MATCHING (cont’d)

- Dynamic range of linac constrained by ability to confine two beams of different energies in the same focusing structure.
- Ratio of linac $E_{\text{inj}}/E_{\text{fin}}$ is constrained so as to avoid underfocusing the high energy and overfocusing the low energy beams.
- Ratio of roughly 10/1 is conservative design choice; depends on linac length and distance between focusing elements.
- Energy ratio in existing designs:
  - JLAB IRFEL: 5/1
  - JLAB FEL UPGRADE: 20/1
  - eRHIC Linac: 10/1

BEAM LOSS

- Loss inside cryomodule $\leq 1 \, \mu A$ (CHL)
- Loss at wiggler entrance $< 1 \, nA$
- Loss everywhere else $\leq 1 \, \mu A$ (BLMs)

$\Rightarrow$ At energies $> 10$ MeV, total beam loss $\leq 2 \, \mu A$

- Scaling from these numbers may be ok, but no detailed model for beam loss exists yet.
Radiation wavelength longer than bunch length: coherent emission.

Both transverse and longitudinal self-forces can cause emittance growth: potentially serious for high brightness beam quality preservation.

Developed the first self-consistent, 2d simulation (R. Li, PAC 1999).

Experimental data from IRFEL and CTF II Facility benchmark code.
RF STABILITY

- RF Control
- RF Instabilities
ENERGY RECOVERY RF PHASOR DIAGRAM
RF CONTROL

![Graph showing Gradient Loop Error Signals vs Frequency [Hz]](image-url)
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.
RF STABILITY FLOW CHART

- Energy Aperture
- Beam loss
- $\Delta P_{\text{light}}$
- $\Delta V_b$
- $\Delta V_c$
- $\Delta F$
- $M_{56}$
- Freq shift
- $\Delta G$
- Phase shift
- Feedback

Jefferson Lab
RF STABILITY MODEL

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

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

- When FEL is off, experimental data from the IRFEL are quantitatively consistent with the model. (With FEL on, model reproduces data only qualitatively.)
HIGHER ORDER MODES & BEAM BREAKUP

- Single-bunch, single-pass effects: limit bunch charge
  - Energy spread induced by variation of longitudinal wakefield across bunch
  - Emittance growth induced by single-bunch transverse BBU (not important for JLab IRFEL)
    ⇒ Minimize strength of impedance source (SRF better!)
- Multibunch, multipass effects: limit average current
  - Transverse and longitudinal HOMs: a stability concern
- Power in HOMs, primarily longitudinal: depends on product of bunch charge and average current
  - Not a hard limit, but may impose design choices to improve cryogenic efficiency
HIGHER ORDER MODES

RF spectra sampled from the input waveguide of a cavity. Black trace: 3.5 mA. White trace: 1.3 mA.

I. Campisi, PAC 1999
HOM POWER DISSIPATION

- For CEBAF cavities, \( k_{\text{loss}} \sim 5.4 \text{ V/pC} \) for \( \sigma_z = 1 \text{ mm} \)
- Power dissipated by the beam is
  \[
  P_{\text{diss}} = k_{\text{loss}} Q \bar{I}
  \]
- For \( I_{\text{ave}} = 0.264 \text{ A} \),
  \( P \sim 5 \text{ kW per cavity} \)
- Induced relative energy spread at 3 GeV is:
  \( \sigma_{E/E} \sim 5 \times 10^{-4} \)
“WHERE HAVE ALL THE LOSSES GONE?”

- The fraction of HOM power dissipated on cavity walls increases with HOM frequency, due to $Q_0 \sim \omega^2$ degradation from BCS theory. It can limit $I_{ave}$ and $I_{peak}$ due to finite cryogenic efficiency.

- We developed a model that estimates fraction of power dissipated on the walls and specifies HOM-power extraction efficiency required.

- We found:
  - > 90% of HOM power is in modes > 100 GHz
  - Power dissipated on the cavity walls is a strong function of bunch length, $\sigma^{-5/2}$
  - “Multiple reflection model suggests that $Q_{ext} \sim 100$ may in fact be possible due to beam pipe openings

- Engineering studies on HOM absorbers are recommended.
MULTIPASS BEAM BREAKUP

- Recirculating beam through a linac cavity can lead to transverse instability
  - Transverse displacement on successive recirculations can excite HOMs that further deflect initial beam
  - Recirculated beam and cavities form a feedback loop
  - For $I > I_{th}$ feedback can be driven unstable
  - Effect is worsened by higher Q’s of modes of a SRF structure
MULTIPASS BBU (cont’d)
MULTIPASS BBU (cont’d)

- TDBBU: 2d beam breakup code used for simulations (Krafft, Bisognano, Yunn)

- Simulations of similar linacs with energy recovery give threshold of ~100 mA

- Typical growth rate of the instability at ~100 mA is ~2 msecs.

- Feedback (similar to B-Factories) possible
LINAC-RING SINGLE BUNCH TRANSVERSE INSTABILITY

- Simulation developed by R. Li during beam-beam studies of linac-ring B-Factories
- Protons and electrons fluid unstable at high disruptions, the “memory” being provided by displacements within proton beam. Looks like cumulative BBU
- When full synchrotron motion included, luminosity decrease was negligible even at large (10-100) electron disruptions
- Based on previous results don’t expect a problem for EPIC, but needs to be checked
CONCLUSIONS

- A self-consistent set of parameters has been developed for an Energy Recovery Linac-on-Proton Ring Collider
- Luminosities of several $10^{32}$ can be attained
- Focused R&D on high current, polarized electrons is strongly suggested
- No major accelerator physics issues are foreseen with the high average currents in energy recovery linacs with SRF technology; however early demonstration experiments would be very useful
- Cornell is seriously looking into the technical possibilities and issues of a high average current, high energy recovery linac for next generation light source (similar parameter space) and JLab is participating. You are not alone!