An Energy Recovery Electron Linac–on–Proton Ring Collider

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Outline

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- Two Scenarios
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- Accelerator Physics Issues of the Proton Ring
- Accelerator Physics Issues of the Energy Recovery Linacs
- Fundamental Luminosity Limitations
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Physics Requirements

- Electron – proton colliders with the following requirements have recently been proposed as a means for studying hadronic structure:
  
  - Center-of-mass energy between 14 GeV and 30 GeV with energy asymmetry of about 1 – 6, which yields $E_e = 3$ GeV to 5 GeV and $E_p = 15$ GeV to 50 GeV
  
  - Luminosity at the $10^{33}$ cm$^{-2}$ sec$^{-1}$ level
  
  - Longitudinal polarization of both beams in the interaction region $\geq 50\% – 80\%$
Two Scenarios

Two accelerator design scenarios have been proposed:

- ring – ring
- linac – ring

Linac – ring option presents advantages with respect to

- spin manipulations
- reduction of synchrotron radiation load in the detectors
- wide range of continuous energy variability

A feasibility study was conducted at Jefferson Lab to determine whether the linac-ring option is viable. A self-consistent set of parameters was derived

Rf power and beam dump considerations require that the electron linac is an Energy Recovery Linac (ERL)
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

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.
Linac–Ring Schematic Layout

Assume linac uses TESLA-style cavities at 20 MV/m and $Q_0 \sim 1 \times 10^{10}$
Point Design 1

- Input parameters: \( E_e = 5 \) GeV and \( E_p = 50 \) GeV
- Assumptions: \( \varepsilon_{n,e} = 60 \) µm at \( Q \sim 1.75 \) nC and \( \varepsilon_{n,p} = 3 \) µm (LHC, RHIC)

- \( N_p \) is set equal to \( 1 \times 10^{11} \) at the Laslett tuneshift limit: \( \Delta \nu_L \leq 0.004 \)
- \( N_e \) is set equal to \( 1.1 \times 10^{10} \) at the beam–beam tuneshift limit: \( \xi_p \leq 0.004 \)
- \( f_c = 150 \) MHz: user driven requirement based on current understanding
- No cooling of proton beam is assumed
- This reasoning yields: \( I_e = 0.264 \) A
  \[ I_p = 2.4 \text{ A} \]
  \[ \sigma_e^* = 25 \text{ µm} \]
  \[ \sigma_p^* = 60 \text{ µm} \]

\[ L = 6.2 \times 10^{32} \text{ cm}^{-2} \text{ sec}^{-1} \]
Point Design 2

- Input parameters: $E_e = 5 \text{ GeV}$ and $E_p = 50 \text{ GeV}$
- Cooling of protons is assumed
- Electrons and protons have equal beam size at the IP
- Electron beam parameters remain the same
- This optimization yields: $I_e = 0.264 \text{ A}$
  $I_p = 2.4 \text{ A}$
  $\sigma_e^* = 25 \mu\text{m}$
  $\sigma_p^* = 25 \mu\text{m}$

$L = 2.1 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$
# Parameter Table

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<th>Point Design 2</th>
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Accelerator Physics Issues of Protons

- Intrabeam scattering: Transverse
  - Point design 1: $\tau_{tr} = 160$ hours
  - Point design 2: $\tau_{tr} = 20$ minutes

- Intrabeam Scattering: Longitudinal
  - Point design 1: $\tau_{tr} = 3$ hours @ $\sigma_E/E=3e-3$
  - Point design 2: $\tau_{tr} = 15$ minutes @ $\sigma_E/E=3e-3$

- Collective Effects
  - Longitudinal mode coupling $\Rightarrow N_p < 6 \times 10^{12}$
  - Transverse mode coupling instability $\Rightarrow N_p < 1.8 \times 10^{12}$

- Emittance growth of the electrons (which have to be recirculated and energy recovered) due to a single collision with the protons $\Rightarrow N_p < 1.5 \times 10^{12}$
Accelerator Physics Issues of ERLs

- Transport Issues
  
  **Linac optics:** two beams of different energies must remain confined in the same focusing channel. A possible solution (I. Bazarov, Cornell University)

- Beam loss: At JLab FEL total beam loss < 1 μA out of 5 mA (60 pC @ 75MHz)
  
  Understanding of generation, modeling and control of beam loss is of great importance!
Higher Order Modes and Beam Breakup

- Single-bunch, single-pass effects: limit bunch charge
  - Energy spread induced by variation of longitudinal wakefield across bunch
  - For TESLA cavities, $k_{\text{loss}} \sim 8.5$ V/pC at $\sigma_z=1$ mm, the induced relative energy spread at 5 GeV is $\sigma_E/E \sim 5 \times 10^{-4}$
  - Emittance growth induced by single-bunch transverse BBU
    $\Rightarrow N_e < 1.5 \times 10^{11}$
  - Minimize strength of impedance source (SRF better!)
Higher Order Modes and Beam Breakup (cont’d)

- Multibunch, multipass effects: limit average current
- Transverse HOMs: a stability concern
  - Recirculating beam through a linac cavity can lead to transverse instability
  - Transverse displacement on successive recirculations can excite HOMs that further deflect initial beam
- TDBBU: 2d beam breakup code used for simulations (Krafft, Bisognano, Yunn). Code not yet benchmarked
- Simulations give threshold of \(~230\ mA\)
- Typical growth rate of the instability is \(~2\ msecs\)
- Feedback (similar to B-Factories) may be possible
Higher Order Modes and Beam Breakup (cont’d)

- Power in HOMs, primarily longitudinal: depends on product of bunch charge and average current
- For $I_{\text{ave}} = 0.264$ A, $P_{\text{diss}} \sim 8$ kW per cavity for $k_{\text{loss}} \sim 8.5$ V/pC at $\sigma_z = 1$ mm
- IR FEL: $I_{\text{ave}} = 5$ mA, $P_{\text{diss}} \sim 6$ W
- Fraction of HOM power dissipated on the cavity walls depends on the bunch length
- It can potentially limit $I_{\text{ave}}$ and $I_{\text{peak}}$ due to finite cryogenic capacity
- A simple analytic model suggests that the fraction on the walls is much less than the fundamental mode load
- Engineering studies on HOM absorbers are highly recommended
Beam-Beam Kink Instability

- The beam-beam force due to the relative offset between the head of the proton bunch and the electron beam will deflect the electrons. The deflected electrons subsequently interact with the tail of the proton bunch through beam-beam kick.

- The electron beam acts as a transverse impedance to the proton bunch, and can lead to an instability.

- In the linear approximation, and disregarding the evolution of the wake within the proton bunch, a stability criterion has been derived [Li, Lebedev, Bisognano, PAC 2001]

\[ D_e \xi_p \leq 4 \nu_s \]

- For the case of equal bunches and linear beam-beam force, chromaticity appears to increase the threshold of the instability [Perevedentsev, Valishev, PRST ‘01].

- The instability has been observed in numerical simulations [R. Li, J.Bisognano, Phys. Rev. E (1993)] during the beam-beam studies of linac-ring B-Factory. The code is presently being used to simulate unequal bunches and a nonlinear force. We also expect chromaticity to be beneficial in this case.
Fundamental Luminosity Limitations

\[ L \propto \xi_p \Delta v_L \frac{\gamma_p^A \varepsilon^*}{C} f_c \]

Luminosity vs. proton beam energy at the Laslett and beam-beam tuneshift limits, for two values of the Laslett tuneshift: 0.004 and 0.04. In both cases \( \xi_p = 0.004 \)
Fundamental Luminosity Limitations (cont’d)

Luminosity vs. proton beam energy at the stability limit of the beam-beam kink instability (linear approximation: $D_e \xi_p \leq 4\nu_s$)
R&D Topics

- High average current (~250mA), high polarization (~80%) electron source
  - State of the art in high average current, polarized sources:
    ~1 mA at 80% polarization [C. Sinclair, JLab]
- High average current demonstration of energy recovery
  - Control of beam loss
  - Multibunch beam breakup instability – Benchmark TDBBU
  - HOM power dissipation
- Electron cooling and its ramifications on Laslett and beam-beam tuneshifts
- Theoretical and if possible, experimental investigation of the beam-beam kink instability
Conclusions

- A self-consistent set of parameters has been developed for an Energy Recovery Linac-on-Proton Ring Collider
- Luminosities of several $10^{32}$ up to $10^{33}$ appear feasible
- No accelerator physics showstoppers have been found. However, several important issues have been identified
- Focused R&D on a number of topics is necessary
- ERL: Cornell University in collaboration with Jefferson Lab, is proposing a high average current (100 mA), high Energy Recovery Linac (5-7 GeV) for a next generation light source and is planning to address some of the technical issues with a smaller scale prototype (100 mA, 100 MeV)
Fundamental Luminosity Limitations (cont’d)

Luminosity vs. proton beam energy at the stability limit of the beam-beam induced head-tail effect (linear approximation).