AN ENERGY RECOVERY ELECTRON LINAC-ON-PROTON RING COLLIDER

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Abstract

Electron-proton colliders with center of mass energies between 14 GeV and 30 GeV and luminosities at the 10^{33} level have been proposed recently as a means for studying hadronic structure [1]. Electron beam polarization appears to be crucial for the majority of experiments. Two accelerator design scenarios have been examined in detail: colliding rings [2] and recirculating linac-on-ring [3]. Although the linac-on-ring scenario is not as well understood as the ring-ring scenario, comparable luminosities appear feasible, while the linac-on-ring option presents a significant advantage with spin manipulations. Rf power and beam dump requirements make the linac-on-ring option viable only if the electron linac recovers the beam energy, a technology demonstrated at Jefferson Lab's IR FEL, with cw current up to 5 mA and beam energy up to 50 MeV [4]. We begin with a brief overview of the Jefferson Lab energy recovery FEL and summarize the benefits of energy recovery. The feasibility of an energy recovery linac–ring collider is investigated and two conceptual point designs are shown. Luminosity projections for the linac–ring scenario based on fundamental limitations are presented. Accelerator physics issues are discussed and we conclude with a list of required R&D for the realization of such a design.

1 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 beam. To date, energy recovery has been realized in a number of different ways [5], [6], [7].

Same-cell energy recovery with cw current up to 5 mA and energy up to 50 MeV has been demonstrated at Jefferson Lab's (JLab) IR FEL and it is used routinely for the operation of the FEL as a User Facility [4]. Microbunches with an rms bunch length of ~20 psec are produced in a DC photocathode gun and accelerated to 320 kV. The bunches are compressed by a copper buncher cavity operating at 1497 MHz. They pass through a pair of superconducting rf (srf) cavities operating at an average gradient of 10 MV/m. The output beam at ~10 MeV is injected into an 8-cavity srf cryomodule where it is accelerated up to ~48 MeV. The beam then passes through the wiggler. Afterward it is recirculated through two isochronous, achromatic bends separated by a quadrupole transport line, back through the cryomodule in the decelerating rf phase and dumped at the injection energy of ~10 MeV. The benefits of energy recovery are:

1. The required rf power becomes nearly independent of beam current.
2. The overall system efficiency is increased.
3. The electron beam power to be disposed of at the beam dumps is reduced by the ratio of the final to injected energy.
4. The induced radioactivity (and therefore the shielding problem) is reduced, if the beam is dumped below the neutron production threshold.

2 CONCEPTUAL DESIGNS

Next we present the reasoning that allows us to develop a self-consistent set of parameters for an electron linac–proton ring collider. Here we consider only the case of 50 GeV protons colliding with 5 GeV electrons. Conceptual designs at different energies [3], and a design based on the existing RHIC storage ring [8] have also been explored. A schematic representation of the electron-proton collider is shown in Figure 1.

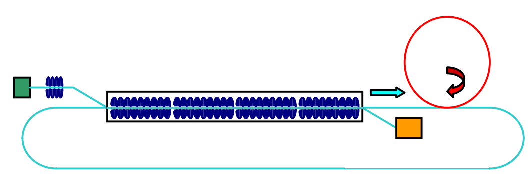

Figure 1. Schematic layout of the electron linac – proton ring collider.

The linac technology assumed here uses TESLA-style cavities, with shunt impedance R/Q=1036 Ohms per cavity and cavity length equal to 1.038m. The residual resistance is ~3 nΩ, equivalent to a Q of ~10^{11}. Considering demonstrated performance from a number of manufacturers, we will assume Q_0 of 1×10^{10} at 2K and accelerating gradient of 20MV/m. At these values the refrigeration power is 40 W/cavity. Thus a 5 GeV linac will require 250 cavities with dissipation due to dynamic losses of 10 kW. Two point designs will be explored. In design 1 both the Laslett and beam-beam tuneshifts will remain below the rather conservative and generally agreed upon value of 0.004. To arrive at a self-consistent set of parameters and a luminosity estimate the reasoning proceeds as follows. We first set the electron beam size at the IP based on projected electron source performance. Then the proton beam parameters are set at the Laslett tuneshift limit. The maximum number of electrons per bunch is determined at the beam-beam tuneshift limit of the protons. Finally effects that influence the choice of the bunch collision frequency are discussed and a choice is made.

An rms normalized emittance of 60 μm for electrons at a bunch charge of 1.75 nC is assumed, yielding a geometric emittance of 6 nm at the interaction point (IP) at 5 GeV. For a beta function of 10 cm the rms electron beam size at the IP is 25 μm. (Round beams are assumed for electrons and protons, not necessarily equal.)

In order for the luminosity not to degrade too much within a collision, the beta function for the proton beam at the IP is set approximately equal to the rms proton bunch length. In this approximation, the Laslett tuneshift can be written as

$$\Delta\nu_L = \frac{N_p}{\sigma_p^{*2}} \frac{r_p}{4\pi\gamma_p^3} \frac{C}{\sqrt{2\pi}}$$

where C is the ring circumference and r_p the classical radius of proton 1.534 x 10^{-18} m. Clearly this tuneshift sets a limit on the ratio of N_p/σ_p^{*2}. Assuming a proton beam rms normalized emittance of 2 μm (consistent with LHC and RHIC specifications), the rms beam size for protons at the IP is 60 μm, for a beta function of 10 cm. Then the number of protons per bunch at the Laslett tuneshift limit of 0.004 is equal to $1\text{x}10^{11}$. The ring circumference is approximately 500m.

The number of electrons per bunch can either be limited by the beam-beam tuneshift of the proton beam or by the single-bunch transverse Beam Breakup (BBU) in the linac [9]. Beam-beam tuneshift of the protons below 0.004 sets the number of electrons per bunch equal to $1.1\text{x}10^{10}$. A simple estimate for the emittance growth due to single bunch BBU in the linac, for an rms bunch length of 1 mm and betatron wavelength in the linac of ~50 m, suggests that the amplification parameter remains less than ~1 if the number of electrons per bunch does not exceed $1.5\text{x}10^{11}$. Should this effect become a serious limit, BNS damping can be used. Therefore, in this case the limit on N_e is set by the beam-beam tuneshift, and not by the single-bunch BBU.

The bunch collision frequency should be maximized subject to the constraints of parasitic collisions, user requirements and possibly the electron cloud effect in the proton ring. We have assumed a bunch separation of 6.66 nsec or 150 MHz repetition rate primarily driven by user considerations as they are presently understood. Clearly a detailed design of the interaction region that satisfies both user requirements and accelerator physics considerations must be carried out in order to determine the optimum value of the collision frequency.

For the case of unequal electron-proton bunch sizes, the luminosity is given by

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

With $N_e = 1.1\text{x}10^{10}$, $N_p = 1.0\text{x}10^{11}$, f_c =150 MHz, σ^*_e =25 μm and σ^*_p = 60 μm, the luminosity is equal to $6.2\text{x}10^{32}$ cm^{-2} sec^{-1}.

Point design 2 utilizes the extremely small emittances that are possible from a linac. It assumes that electron cooling of the protons results in proton beam size at the IP equal to the electron beam size, 25 μm. The proton bunch population remains at $1\text{x}10^{11}$ similar to LHC and RHIC. The Laslett tuneshift is now equal to 0.024 and the electron beam parameters remain the same as in design 1. This parameter set yields a luminosity of $2.1\text{x}10^{33}$. The average current in the linac of 0.264 A and the average current in the ring of 2.4 A. Table 1 summarizes the parameters for the two point designs.

Table 1: Parameter table for linac-ring scenarios

Parameter	Units	Design 1	Design 2
E_e	GeV	5	5
E_p	GeV	50	50
N_e	ppb	$1.1\text{x}10^{10}$	$1.1\text{x}10^{10}$
N_p	ppb	$1.0\text{x}10^{11}$	$1.0\text{x}10^{11}$
f_c	MHz	150	150
σ^*_e	μm	25	25
σ^*_p	μm	60	25
ε_e	nm	6	6
ε_p	nm	36	6.25
β^*_e	cm	10	10
β^*_p	cm	10	10
σ^p_z	cm	10	10
σ^e_z	mm	1	1
ξ_p	–	.004	.004
$\Delta\nu_L$	–	.004	.024
D_e	–	.78	4.6
I_e	A	.264	.264
I_p	A	2.4	2.4
L	$\text{cm}^2\text{sec}^{-1}$	$6.2\text{x}10^{32}$	2.1 x 10^{33}

3 ACCELERATOR PHYSICS ISSUES OF THE PROTON RING

We examine transverse and longitudinal intrabeam scattering and collective effects. Estimates of the emittance growth of the electron beam due to a single collision with the protons, although not a proton issue, will also be given here, as it may impose a limit on the proton bunch population.

3.1 Intrabeam Scattering (IBS)

To calculate the diffusion rates we follow the treatment of reference [10]. At 50 GeV for the parameters of point design 1, the diffusion time of both transverse and longitudinal IBS is approximately 20 minutes, which implies that electron cooling with cooling rate of similar magnitude is required. While technically challenging, such cooling appears feasible. For point design 2 the rate for transverse IBS is ~16 secs and for longitudinal IBS is ~1.5 minutes. The required increase of damping decrements could possibly be achieved not only by an increase of the electron beam current but also by better shaping of the beam.

3.2 Collective Instabilities

The longitudinal mode coupling or microwave instability, for $|Z_P/n|$ ~0.25 Ω consistent with LHC [11] and the Tevatron [12], limits the number of protons per bunch to to ~6x10^{12} . The transverse mode coupling instability, limits the proton bunch population to ~1.8 x 10^{12}, for $|Z_\perp|$ ~ 5 x 10^4 Ω (scaled from LHC). In conclusion, both types of instabilities occur at proton bunch populations above the design parameters we chose.

3.3 Electron Beam Emittance Growth due to a Single Collision

A single collision disrupts the electron beam and causes emittance growth. In an energy recovering linac, the electron beam with degraded phase space has to be recirculated for energy recovery. Deceleration in the linac cavities can result in scraping and beam loss due to adiabatic antidamping. Therefore, the amount of tolerable beam loss at the linac exit (where the beam size is largest) imposes a limit on the tolerable emittance growth due to a single collision. This, in turn, imposes a limit on the number of protons per bunch.
Let us assume that the maximum tolerable beam loss is 4 x10^{-6} which corresponds to 1 μA out of 250 mA, based on Jefferson Lab experience. Assuming a gaussian distribution of the electrons, aperture size of 7 cm and an average beta function in the linac of ~50 m, the maximum rms normalized emittance, consistent with this amount of beam loss is calculated to be 800 μm. In the small disruption limit, the emittance growth of the electron beam due to a single collision with the proton beam of intensity N_p is given by [13]:

$$\varepsilon_n^2 = \varepsilon_{0,n}^2 + (0.194 r_e N_p)^2$$

For $\varepsilon_{0,n}$=60 μm, ε_n = 800 μm, N_p has to be less than 1.5 x 10^{12} particles per bunch, well below our design specification.

4 ACCELERATOR PHYSICS ISSUES OF THE ENERGY RECOVERY LINAC

We will examine accelerator transport issues, Higher Order Mode (HOM) power dissipation and BBU phenomena. We will briefly discuss the beam-beam kink instability and present a stability condition in the linear approximation.

4.1 Accelerator Transport

Energy Recovery Linacs (ERLs) must have the ability to confine two beams of different energies in the same focusing structure. Lack of this ability may impose a constraint on the ratio of injected to final beam energies. A linac optics design has been devised for injection energy of 10 MeV and final energy of 5 GeV [14,15], in a single pass linac, using TESLA cavities operating at a gradient of 20 MV/m. Focusing is provided by triplets placed between cryomodules and the beta functions in both planes do not exceed ~60 m. This linac design is optimised for high multipass BBU threshold, as we will see later.
Understanding the origin of and being able to control beam loss are crucial in an ERL with the parameters outlined above. In the JLab IRFEL several indicators place an upper limit on the amount of beam loss in the recirculator to 2 μA out of 5 mA. This amount of loss, although extremely small may be unacceptable for the ERL design discussed here, as it can potentially give rise to hundreds of kW of uncontrolled, lost beam power. More work is required to understand both the origin of the loss and possible cures.

4.2 HOM Power Dissipation

Power in HOMs, primarily longitudinal, depends on the product of bunch charge and average current and could present a serious enough constraint that engineering choices are imposed for improved cryogenic efficiency. The power dissipated by the beam in HOMs is given by

$$P_{diss} = 2 k_p Q \bar{I}$$

where the factor of 2 accounts for the two beams in the linac (accelerating and decelerating). For TESLA cavities, the calculated loss factor is equal to 8.5 V/pC for 1mm rms bunch length, therefore the power dissipated by the beam for average current of 0.264 A is approximately 8 kW per cavity. It is important to address the question of where these losses go. An analytic model [16] suggests that, for the parameters quoted here, a small fraction of the total power, of the order of a few Watts, is expected to be deposited on the cavity walls. Engineering studies on HOM cooled absorbers between cavities or cryomodules are needed. Furthermore, the longitudinal wakefields affect the energy of the particles along the bunch, inducing a correlated energy spread. The induced rms energy spread at 5 GeV is approximately 5.7×10^{-4} for the loss factor of the TESLA cavities.

4.3 Beam Breakup

BBU refers to a variety of collective phenomena that can limit the performance of srf energy recovering linacs. These coherent effects include single-bunch, single-pass phenomena which limit the charge per bunch, and multi-bunch phenomena which limit the average current. Single bunch effects include energy spread induced by longitudinal wakefields, and emittance growth induced by transverse wakefields across the bunch. Both effects were discussed earlier.

Multipass, multi-bunch BBU occurs when a recirculating beam through a linac cavity leads to a transverse instability. Transverse beam displacement on successive recirculations can excite HOMs that further deflect the initial beam. The recirculated beam and cavities form a feedback loop, which, for beam current greater than the threshold current of the instability, can be driven unstable. The effect is worse in srf cavities because of the higher Q's of the HOMs. The threshold current depends on various cavity and lattice parameters, including the Q's, frequencies and R/Q's of the HOMs, the beam energy, the beta functions and phase advance in both planes and the recirculation path length.

A two-dimensional simulation code, TDBBU [17] has been developed for the calculation of the threshold current in an actual machine configuration. TDBBU simulations for the 5 GeV ERL linac with the optics developed by Bazarov and discussed earlier and HOM data from the 9-cell TESLA cavities [18], resulted in a threshold current of about 205 mA [14,15]. This threshold, although remarkably high, is still below the average current of our parameter sets. However the typical growth rate of the instability just above threshold is in the msec range, allowing for the possibility of using feedback for the control of the instability.

4.4 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 will then interact with the tail of the proton bunch through the beam-beam kick. The electron beam acts similar to a transverse impedance for the proton bunch and can drive the protons unstable. In the linear approximation and disregarding the evolution of the wake within the proton bunch, a stability criterion has been derived [19] which places an upper limit on the product of the electron beam disruption parameter D_e and the beam-beam tuneshift of the protons ξ_p :

$$D_e \xi_p \leq 4\nu_s$$

where ν_s is the synchrotron tune of the proton beam. According to this stability condition, design 1 is a factor of 7 below the threshold and design 2 is a factor of 1.3 below the threshold for ν_s equal to 6×10^{-3}.

Recently a simulation study was performed for the case of bunches of equal bunch length and a linear beam-beam force and chromaticity was found to increase the stability threshold [20]. This instability has been observed in numerical simulations during the beam-beam studies of a linac-ring B-Factory at Jefferson Lab [21]. The code is presently being used to simulate the more realistic case of unequal bunches and a nonlinear beam-beam force.

5 FUNDAMENTAL LIMITATIONS

5.1 Luminosity at the Laslett and Beam-Beam Tuneshifts Limit

The Laslett and beam-beam tuneshifts impose fundamental limitations on the proton and electron bunch intensities. The luminosity of an electron linac-on-proton ring collider can be expressed in terms of the Laslett and beam-beam tuneshifts as follows:

$$L = \left(\frac{4\pi\sqrt{2\pi}}{r_p^2} \right) \xi_p \Delta\nu_L \frac{\gamma_p^4}{C} \frac{\sigma^{*2}}{\beta^*} f_c$$

Figure 2 is a plot of luminosity vs. proton beam energy for a beta function at the IP β^* =10 cm, an rms beam size at the IP σ^* = 40 μm and collision frequency f_c = 150 MHz. The ring circumference C has been minimized subject to the engineering constraint of maximum magnetic field (in this case B=4 Tesla). The red curve corresponds to $\Delta\nu_L$ = 0.004, which is a generally accepted value for the Laslett tuneshift without cooling. The green curve corresponds to $\Delta\nu_L$=0.04, achievable by cooling and consistent with the value assumed in the ring-ring scenario [2].

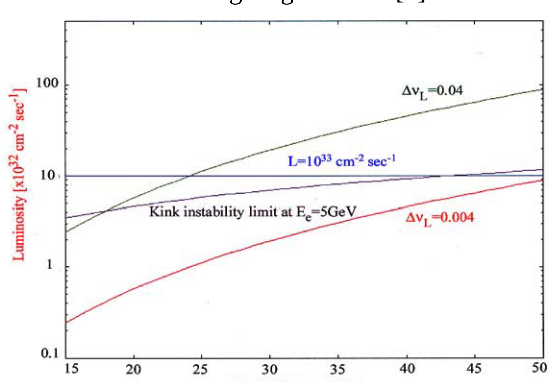

Figure 2. Luminosity vs. proton beam energy at the Laslett and beam-beam tuneshift limits, for two values of the

Laslett tuneshift: 0.004 and 0.04. In both cases the beam-beam tuneshift is 0.004.

In both cases ξ_p =0.004. The horizontal line corresponds to luminosity equal to 1.0×10^{33} cm^{-2} sec^{-1}. Note that luminosity at the 10^{33} level is not attainable with proton beam energies up to 50 GeV as long as the tuneshifts remain below 0.004. Furthermore, if the Laslett tuneshift can be raised to values that exceed 0.004, then luminosity at the 10^{33} level is possible only for proton beam energies above ~25 GeV.

5.2 Luminosity at the Beam-Beam Kink Instability Limit

The beam-beam kink instability is an additional effect, which could potentially impose a limit on the luminosity of linac-ring colliders. In the absence of more accurate results at the present time, we will use the analytic criterion presented above to re-write the luminosity at the stability limit of the beam-beam kink instability as:

$$L = \left(\frac{4}{r_e r_p} \right) \gamma_e \gamma_p \nu_s \sigma'^{*2} f_c$$

The purple curve of Figure 2 is a curve of luminosity vs. proton beam energy for 5 GeV electrons as given by the above equation. The synchrotron tune has been set equal to 1×10^{-3}, the rms angular divergence of the beam at the IP, $\sigma'^{*} = \sigma^{*} / \beta^{*}$ = 40 μm/10cm= 0.4 mrad and the collision frequency f_c =150 MHz. This curve, although pessimistic, given that it has been derived based on a crude approximation, it nevertheless demonstrates the potentially detrimental effect this instability could have on reaching the desired luminosity and therefore the need for a thorough investigation of the instability.

6 R&D TOPICS AND CONCLUSIONS

Preliminary results of a feasibility study of an energy recovering electron linac on a proton ring collider are presented. Luminosities at the 10^{33} level appear attainable and the linac-on-ring scenario presents a significant advantage with respect to spin manipulations, energy variability and synchrotron radiation power loading of the detectors. No showstoppers have been found but a number of important issues have been identified that would require focused R&D before such a facility is designed and built. These topics include: a) High current polarized electron source [22,23]; b) High current (~100 mA) demonstration of energy recovery, which includes understanding and controlling beam loss, benchmarking TDBBU and possibly developing feedback for the multibunch BBU instability, and understanding of HOM power dissipation issues; c) Electron cooling and its ramifications on Laslett and beam-beam tuneshifts and d) Theoretical and, if possible, experimental investigation of the beam-beam kink instability and feedback. Recently, recirculating, energy-recovering linacs have attracted much attention and are being considered for a number of applications, such as drivers for synchrotron radiation sources [24], and high average power FELs. A number of the listed R&D topics, especially those related to the energy recovery of high average currents, are being pursued by these communities, so it is safe to assume that progress will be rapid in these directions.

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