AN EFFICIENT HIGGS FACTORY: THE LINEAR GHOST COLLIDER

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Abstract

A 550 GeV centre-of-mass Higgs factory is presented, the Linear Ghost Collider (LGC). Acceleration and deceleration are performed within SRF linacs where the bunches transported are net neutral, comprising equal charges of electrons and positrons, termed ghost bunches. Within these, one charge partner accelerates, and the other decelerates. Energy is recovered after a collision, and all particles recycled. An accompanying paper - Ghost Collider (GC) - introduces this concept. LGC comprises an alternative configuration to GC that eliminates turn-around arcs. This enables a large reduction in energy lost to synchrotron radiation, and in bunch degradation, in comparison to GC. Two variants of LGC are presented: a pulsed version realisable with proven SRF technology with instantaneous luminosity $35\times\ 10^{34}$ cm^{-2} s^{-1} @ 100 MW electrical power; and a continuous-wave (CW) version based on expected parameters for thin-film Nb_3Sn-on-copper SRF technology, capable of 348×10^{34} cm^{-2} s^{-1} @ 160 MW electrical power.

DRIVE BUNCHES

In the original GC proposal [1] ghost bunches are formed by low-energy injected bunches of one charge partnered with collision energy spent bunches of the other. These then exchange energies as they pass through the linac, thus GC is a new type of energy recovery linac (ERL), one where energy recovery is intra-bunch. This eliminates to first order the generation of higher-order modes (HOM) within the cavities, thereby negating a key concern with high-current ERLs. A disadvantage of GC topology is that injection must be co-located with extraction from the interaction points (IPs), necessitating two turn-around arcs at half the collision energy, one at each end of the facility. This is expensive in terms of synchrotron radiation (SR) loss (which must be replaced), and concomitant beam quality degradation from emittance and energy spread increase (which must be damped before re-use of bunches).

The concept of intra-bunch energy recovery allows a reconfiguration to enable better performance through the elimination of turn-around arcs. To do this, one must first recognise that it is only necessary that each charge partner in a ghost bunch have matching velocities, not energies. For electrons and positrons, this is always the case provided their energies are more than a few GeV. Secondly, it is not necessary that both charge partners undergo collision, and therefore, only one partner needs to be accelerated to full collision energy. This allows each linac to be split into **n** stages, shown in Fig. 1. Over the **n** stages one charge partner, the *colliding bunch*, achieves collision energy E_{coll}, passes through multiple IPs in series, and is then decelerated to injection energy E_{inj}; whereas the set of **n** charge partners - termed *drive bunches* - are only decelerated and accelerated between E_{inj} and $E_{drive} \equiv (E_{coll} - E_{inj})/\mathbf{n} + E_{inj}$[1].

This process is illustrated sequentially in Fig. 2 for the arbitrary choice $\mathbf{n} = 4$. Only ghost bunches containing right-going colliding positrons are shown; simultaneously, there will also be ghost bunches containing right-going colliding electrons, one-half RF cycle separated from them. By default, counter-propagation of ghost bunches within each linac is allowed, leading to a further two sets of ghost bunches containing; left-going colliding electrons; and positrons. There are therefore another three equivalent illustrations of Fig. 2.

Drive bunches are transported in bypass lines parallel to the linac within the tunnel, being kicked into and out of partnership with their partner colliding bunch in turn. During acceleration of the colliding bunch, **n** drive bunches are decelerated from E_{drive} to E_{inj}, with the reverse occurring upon deceleration. Chicane delays to enable the formation, collision, and splitting of high-energy charge partner ghost bunches are reproduced from GC. Colliding bunches never experience an arc, thus LGC is a truly linear collider. The drive bunches must be recirculated at E_{drive}, enumerated for various values of **n** in Table 1.

SR SCALING WITH n

As power lost to SR when bending goes as the fourth power of the energy, and normalised emittance degradation as the fifth power, the decrease in energy loss of recirculating bunches more than compensates for the linearly increasing drive beam current as a function of **n**. In comparison to the half-collision-energy turn-around arcs of GC, the power lost to SR in **n** bunches at E_{drive} in an identical arc is $2^4/\mathbf{n}^3$, and the concomitant emittance degradation is $2^5/\mathbf{n}^5$. However, instead of keeping the large arc size of GC, it is chosen to sacrifice some of this gain in order to scale the drive beam recirculation arc radii in proportion to E^2; an accepted standard that balances cost with SR power [2], resulting in a smaller facility footprint. Including this, the loss per turn $\Delta E \propto E^4/R$ so $\Delta E_{LGC}/\Delta E_{GC} = 2^2/\mathbf{n}$. The drive beam emittance degradation $\Delta\epsilon \propto E^5/R^{3/2}$ so $\Delta\epsilon_{LGC}/\Delta\epsilon_{GC} = 2^2/\mathbf{n}^2$. The resulting arc radii and SR loss per turn are

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[1] E_{inj} for colliding bunches is not necessarily equal to E_{inj} for drive bunches, it is chosen to make them equal to minimise beam transport.

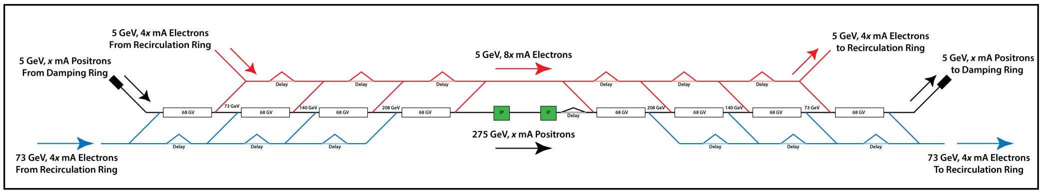

Figure 1: Layout of Linear Ghost Collider for example **n** = 4 stages.

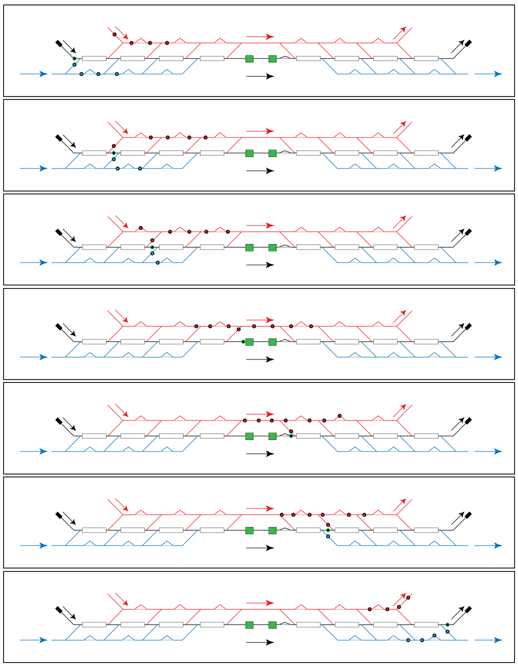

Figure 2: LGC collision sequence for example **n** = 4. Right-going colliding positrons only.

enumerated in Table 1. It is judicious to note that a value of **n** > 6 results in drive recirculation rings smaller than the damping rings developed for the ILC [3] with R = 515 m. LGC therefore adopts a *single ring tunnel* at each end of the linac containing **both** damping and recirculation rings, and restricts **n** ≥ 6. Table 2 shows the resulting SR loss as a function of **n** for tunnel of radius 515 m.

Two observations can be made: LGC resembles a classic current transformer, but the transformer medium is intra-bunch energy recovery; and provided sections are reserved for each changeover zone, LGC could serve as an upgrade to LCF [4] with the caveat that a damping / recirculation ring should be at each end, not centrally located.

TIMING & DELAY LINES

Each drive bunch must be individually coincident with its colliding bunch charge partner. Therefore drive bunches should be injected ahead of the colliding bunch and sequentially brought into coincidence through a series of delay chicanes. The drive bunches used to accelerate the colliding bunch cannot be immediately re-used to decelerate the same bunch, as they will be behind it. Instead, the bunches that decelerated in a previous collision cycle must be used. One option for achieving this is used for the illustration of Fig. 2.

Table 1: For E_{coll} = 275 GeV and E_{inj} = 5 GeV as a function of **n**: E_{drive}; arc radius; and resulting SR loss per arc under a scaling $\propto E^2$ if the original GC turn-around arc radius at 140 GeV has that equal to LEP / LHC.

n	E_{drive}[GeV]	R[m]	SR loss [MeV]
3	95.0	1612	3662
4	72.5	939	2060
6	50.0	447	916
8	38.8	269	515
16	21.9	86	129

Table 2: Fixing the arc radius to that of ILC damping rings (515 m) to enable a shared tunnel: E_{drive}, for example **n** ≥ 6; and resulting SR loss per arc.

n	E_{drive}[GeV]	SR loss [MeV]
6	50.0	806
8	38.8	292
12	27.5	74
16	21.9	30

Here drive bunches at E_{inj} to be accelerated and are injected co-propagating, but ahead of any spent bunches from the acceleration cycle, and bypass the IPs before being employed to decelerate the colliding bunch. Upon completion of one collision cycle, each **n** drive bunch has exchanged energy in passing from left to right.

EMITTANCE & ENERGY SPREAD

In LGC the only significant contributor to energy spread and emittance degradation is the delay chicane required at E_{coll}. The evolution of emittance and energy spread in GC and LGC through a collision cycle are compared in Fig. 3.

CHANGEOVER ZONES

Each linac will contain **n** − 1 changeover zones - where E_{inj} spent drive bunches are extracted and E_{drive} fresh drive bunches are injected prior to collision, and the reverse after collision. At each changeover zone the requirements are for accelerating / decelerating colliding bunches respectively: E_{inj} electron and positron bunches are extracted / injected to low energy bypasses; E_{drive} electron and positron bunches are injected / extracted from high energy bypasses; right-

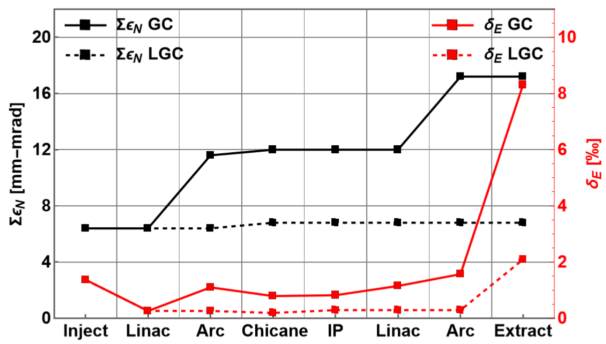

Figure 3: Sum of normalized transverse emittances (black) and rms energy spread (red) of colliding bunches for GC (solid) and LGC (dashed).

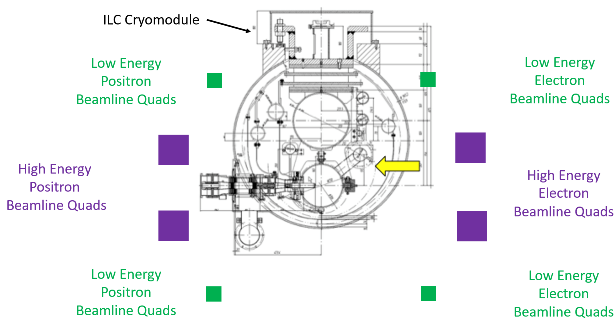

Figure 4: Eight-axis transverse bypass layout.

going and left-going injection / extraction occupy common zones; path length between injection / extraction must be λ_{linac} longer then in the linac, with each injected / extracted bunch at the back of the train of **n** bunches; injection / extraction must be downstream of extraction / injection; each orbit bump must be closed, so the first injection / extraction magnet is $m\lambda_\beta/2$ downstream of the last extraction / injection magnet, for $m \in \mathbb{Z}$. The bypasses must avoid the cryomodule support structures and RF input waveguides. The cheapest option would be to rotate the injection / extraction lines by $\pm 45°$ with respect to horizontal, providing 4 axes for the 8 beams. However this may be difficult to engineer, therefore it is chosen to rotate beamlines by $\pm 15°$ and $\pm 45°$ respectively, providing 8 separate axes, illustrated in Fig. 4.

LUMINOSITY & DISRUPTION

What we term as the ghost bunches at the IPs, where both charge partners are at collision energy (having been combined utilising the $\lambda/2$ delay chicane), has been considered previously under the name *charge compensation of beamsstrahlung* [5–10]. These indicate a charge separation instability at IPs for disruption parameter $\gtrsim$ 10. A similar second-order instability at parasitic crossings within the linac is under investigation. Mitigation may be possible; if not, LGC would eliminate linac counter-propagation by reverting to twin-axis linacs analogous to ERLC [11], with a construction cost penalty. Round beams are chosen as they give higher luminosity than flat beams for a given disruption.

PULSED & CW PERFORMANCE

Using parameters in Table 3, luminosity per bunch crossing can be up to $9.1 \times 10^{29}\text{cm}^2$. It should be noted that this is for the sum of e^+e^-, e^+e^+, and e^-e^-. The disruption parameter $r_e N_b \sigma_z / \gamma \sigma_r^2 = 2.25$. For CW RF the limitation is the equilibrium energy spread; reducing this implies disruption is reduced to 1.48. Electrical power consumption for these luminosities is estimated in Table 3. A 50% efficiency wallplug to RF is assumed, as is cryogenic efficiency of 900 W/W at 2K and 230 W/W at 4K. In the pulsed case, one must pre-accelerate drive bunches at the start of each pulse; this dominates total power. In the CW case, this is not necessary, and the limit becomes cryogenic power.

Table 3: LGC Parameters for Pulsed RF with Proven 2K SRF; and for CW RF with Predicted 4K TF-SRF Technology

Parameter	**Unit**	**Pulsed LGC (140 Hz)**	**CW LGC**
COM	GeV	550	550
# IPs	#	4	4
# Stages	**n**	8	16
E_{inj}	GeV	5	5
E_{drive}	GeV	39	22
Gradient	MeV/m	31.5	31.5
Length	km	35	35
Cavity Q_0	10^{10}	2.7	5.4
Bun. Pop.	10^{10}	2 + 2	2 + 2
Bun. / Train	#	1312	-
Train length	µs	180	-
Current / beam	mA	-	9.3
CW collision rate	MHz	-	1.45
Bun. Spacing	ns	277	689
$\varepsilon_{Nx/y}$	nm-rad	3.8 / 3.8	5.7 / 5.7
$\beta^*_{x/y}$	mm	2 / 2	2 / 2
$\sigma_{x/y}$	nm	118 / 118	146 / 146
Disruption	-	2.25	1.48
Fac. Lumi. 10^{34}	$\text{cm}^{-2}\text{s}^{-1}$	35	348
P. Damp. Ring RF	MW	13	13
P. SR Loss	MW	8	55
P. Linac RF	MW	0.3	12
P. Cryo.	MW	14	71
P. Drive Beam	MW	62	0
Total Power	MW	100	160

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