HOW TO RECOVER ENERGY IN LINEAR COLLIDER

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Abstract

A scheme of designing a linear collider with an energy recovery is discussed.

INTRODUCTION

A linear accelerator (linac) is tremendously power hungry. Besides costly initial investment for RF power related equipments to ensure the capacity of high RF power required for the linac in the construction phase, the cost of delivering RF power to accelerate beam is a major portion of operational cost of any linear accelerator. Indeed it is one of the major limiting factors for building large scale high current high energy linacs. As a result accelerator builders are constantly looking for a way to reduce the RF power demand of an accelerator.

Recently energy recovery in a recirculating linac has turned out to be one of the most promising ways to significantly improve the efficiency of RF power usage in an accelerator. This was demonstrated in the IR-FEL Demo project at the Jefferson Lab in 1999 [1]. This technology has excited world since then producing several high current accelerator projects for various goals which became feasible because of this innovation. In a traditional energy recovery scheme an electron beam (it can be any other particle beam) is first accelerated to a final energy (this can be done in one pass or multiple passes) and experiments are performed with the beam. Then the spent beam is brought back to the beginning of linac to by transport channel specifically built for the recirculation for deceleration. This recirculation beam line is a nontrivial addition to the facility in cost and space. However, we observe that the standard configuration of a linear collider allows a different way of energy recovery scheme by bringing the spent beam to the back end of the linac which requires a significantly less modification in beam transport lines. In this note we propose a novel way of building such a linear collider with an energy recovery (ERLC).

A LINEAR COLLIDER WITH AN ENERGY RECOVERY

A linear collider in its most simplified form consists of two linacs on a straight line where beam 1 is accelerated through linac 1 starting from one end and beam 2 through linac 2 from the opposite end. Then beam 1 and beam 2 are brought to a collision at an interaction point and spent beams are dumped. A conventional way of energy recovering would be to bring beam 1 after the collision back to the beginning of linac 1 and to decelerate the beam through linac 1. And similarly for beam 2. Besides for additional long recirculation beam lines the cost of which significantly reduces advantage of recovering energy it may be extremely difficult, if not impossible, to transport two beams together in a high energy collider. Instead we propose an energy recovery by decelerating beam 1 through linac 2 and beam 2 through linac 1. Cavities in linac must be configured such a way that beam can be accelerated by entering either left or right at the same time. This can be done. The problem is to avoid collisions between accelerating beam and decelerating beam in linacs. This can be arranged by judiciously selecting the length and the repetition rate of macro pulses. To see this let us consider the following simplified case. Assume two identical linacs each consisted of n accelerating sections of length L with a spacing of length D between sections. Let d be the length of the interaction region between two linacs which accommodates detectors and collision point (to be more precise d is the path length of each beam in the interaction region). If one selects $d = 2m(L+D)-D$ and the distance between macro pulse is equal to $2(L+D)$, one can be assured that accelerating and decelerating beams will not encounter each other in accelerating sections. Two beams may be arranged to follow separate paths in the drift section between two accelerating sections, for example by a chicane to avoid direct collisions. Dipole magnets are sufficient to assemble the chicane for an e^--e^- collider. However, RF separators (or something similar to that functionally) will be required for an e^--e^+ collider.

As an example of ERLC being proposed here we briefly describe a machine performance of a 200 GeV electron-positron (or electron) collider in the following. Let us choose L = 2.5 km, D = 1.0 km and d = 6.0 km. Each linac consists of two accelerating sections and a drift section between them. For accelerating cavity we take parameters from the CEBAF superconducting cavity operating at 1.5 GHz with the loaded Q of 6.6×10^6. Therefore, ideally a macro-pulse may contain up to 5000 bunches with the inter-bunch spacing of 20 cm. In this example we are far less aggressive. Beam parameters chosen are listed in Table below. Note that the β* value of 5 mm could be lower considering the short bunch length. It is one of the most efficient ways of enhancing the luminosity if beam dynamics can tolerate. Bunch can be quite short in linac. At Jefferson Lab an electron bunch rms length is typically about 100 μm.

Energy per beam	100 GeV
Number of electrons (or positrons) per bunch	5×10^9
Normalized emittance (rms)	2 mm-mrad
Bunch length (rms)	≤ 1 mm
Number of micro-bunches in a macro-pulse	900
Inter-bunch distance	1 meter
Repetition rate of macro-pulses	43 kHz
β* at collision point	5 mm
Luminosity	1.5×10^{35} /cm^2/s

Average beam current in this illustration is 30 mA and the beam power at the interaction region is 3 GW. Assuming the effective cavity gradient of 20 MV/m in the accelerating section a minimum of 600 kW of RF power per meter must be delivered to accelerate beam without an energy recovery (6 GW in total). Power dissipation through the cavity wall due to residual resistivity of superconducting niobium is about 40 W/m assuming the unloaded cavity Q of 10^{10}. A higher gradient value like 35 MV/m is attractive from the viewpoint of enabling a shorter linac. However, a quadratic dependence of cryogenic load to the cavity gradient can quickly become prohibiting. A detailed optimization study is needed of course. Deceleration of beams can stop at 100 MeV for example and we only need to design a beam dump facility which can accommodate only 3 MW of beam power. Since accelerating and decelerating beam at cavity have the same energy it is much easier to transport them together optically in ERLC compared to existing energy recovery linacs where two beams of substantially different energy especially at the front and back end of linac present a challenging problem in designing transport optics. It will be worthwhile to try deceleration to much lower beam energy.

We also note that the example linear collider can be made even simpler. Each linac can be consisted of a single long (5 km for instance) accelerating section instead of two accelerating sections and interaction region can occupy as much space as required and available. In this situation the efficiency of energy recovery will suffer slightly in principle due to a lower macro-pulse repetition rate. Beam separation chicane in linac is not required any more.

A PARTICLE RECOVERY SCHEME

Energy recovery linac recovers most beam energy but all particles constituting beam are thrown away. Therefore, a heavy burden is put on the gun to deliver high charged bunches either continuously or quasi-continuously because energy recovery makes sense the most in cases where large average beam currents are required. It may be possible to recycle beams by adding a small low energy ring at the front end of each linac where synchrotron radiation is causing no trouble. Decelerated beam may be injected into the ring instead of being dumped and then is reinjected to the linac from the ring after a circulation. The whole accelerator structure would resemble a shape of Q-tips.

ISSUES AND CONCLUSIONS

It appears to be possible to eliminate RF power consumption as the major limiting factor in designing high current linac adopting an energy recovery scheme. Electric power demand by cryogenic facility to handle heat from cavity wall loss as we push for a higher gradient to reduce the cost of linac is obviously the next major limiting factor. Furthermore, high current linac with a large bunch charge generates a huge amount of beam power loss caused by machine impedances. It is particularly important to remove the HOM power loss from cavity with minimal addition to cavity cryogenic load.

As for gun which can deliver a large amount of electrons continuously DC photocathode gun is promising presently because of its demonstrated capability for cw operation with a large current. The Jefferson Lab IR-FEL upgrade project will be operating at the average current of 10 mA with a DC gun producing the bunch charge of 135 pC. There exists a light source project which aims for 100 mA current with the same type of DC gun [2]. Sometime ago we carried out design study of a low emittance injector based on a DC photocathode gun with promising results for bunch charge ranging from 100 pC to 2 nC [3]. We should note that normalized emittance of 2 mm-mrad for the bunch with 800 pC listed in Table earlier is yet to be demonstrated in a DC gun based injector design though it is reasonable to expect a substantial improvement on our results with more concerted efforts. With RF photocathode gun such an emittance is already achievable but delivering cw current in tens of mA is an issue.

We conclude that energy recovering linear collider has a potential for making high energy experiments demanding an extremely large luminosity possible.

REFERENCES

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[2] S. Gruner et al., Rev. Sci. Inst., **73**, 1402 (2003).
[3] B. C. Yunn, “High Brightness Injectors based on Photocathode DC Gun”, Proc. of 2001 Particle Accelerator Conf., 2254 (2001).