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SCALING THE TBNLC COLLIDER DESIGN TO HIGHER FREQUENCIES*

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Abstract

The TBNLC collider design uses Relativistic Klystron Two-Beam Accelerator (RK-TBA) units as the rf power source for a NLC-type linac at 11.4 GHz. In this paper we report on a simple analysis of using RK-TBA units as a rf power source for a CLIC-type linac at 30 GHz. The desired rf macropulse duration is less than 50 ns with a repetition rate of 600 Hz. We propose to use magnetic pulse-compression units driving ferrite-core induction cells for this system. Many elements of the TBNLC remain the same for a collider design at this higher frequency.

Introduction

In this paper we described a short-pulse rf source that could be used to drive an electron-positron collider. We refer to this design as RK-CLIC. The high-gradient structures being considered are about 1.5 times longer, with a longer fill time, than those that CLIC proposes for their 10-bunch collider design [1]. Each main linac accelerating structure requires 95 MW to produce an average loaded accelerating gradient of 80 MV/m. The structures are 42 cm long and 8 cm are allowed for pumping ports, flanges, etc., resulting in a 0.5 m spacing. Thus, the average gradient is 67 MV/m for a total main linac length of 15 km to produce a 1-TeV center-of-mass energy. The high-gradient linac beam profile is a 50 bunch train with a 20 cm spacing. The linac will operate at 600 Hz to achieve a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. The rf pulse shape has a 17-ns linear ramp with a 33.7-ns flat top to produce a constant energy for all the bunches at the interaction region.

In analogy to the TBNLC [2], we propose that the high-gradient linac be powered by 50 RK-CLIC units. Each unit provides rf power for 300 meters of main linac. Similar to the TBNLC, each unit consists of the following major components: a 1.2-kA, 2.5-MeV induction injector, a beam modulation unit, an adiabatic capture section to accelerate and bunch the beam, the main rf power extraction unit, and an afterburner where power is extracted from the decelerating beam prior to the beam dump. At the entrance to the rf power extraction unit the beam has an average energy of 10 MeV and 1,120 A of rf current. A one meter section of the rf power extraction unit is shown in Fig. 1. Each rf power extraction unit is comprised of about 300 of these sections, and each section drives two high-gradient linac accelerating structures.

Drive Beam Dynamics Issues

The drive beam dynamics issues of concern are beam transport, longitudinal bunch stability, and transverse beam instabilities.

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Fig. 1. A 1-m section of the RK-CLIC rf power extraction unit. There are 300 of these sections powering 600 linac accelerating structures for each RK-CLIC unit.

Drive Beam Transport

We use permanent magnet quadrupoles in a FODO lattice for beam transport. The lattice period is 33.3 cm with a 60° phase advance per period to produce a 2-m betatron period. The ferrite magnets have a 800 G pole strength, 2.5 cm radius bore, and a 0.48 occupancy factor.

For a 500 π-mm-m normalized edge emittance, the drive beam edge diameter should be about 3 mm. This is produced by the 30 GHz rf output structures is 6 mm. This places a high emphasis on the production and preservation of low emittance beams. The emittance requirement could be relaxed by increasing the drive beam energy.

Longitudinal Bunch Stability

We use a transverse chopper to initially modulate the drive beam as in the TBNLC design. However, other modulation schemes can be envisioned. The beam exits the chopper occupying a longitudinal phase of 240° and is compressed to 70° reaching an rf current of 1,120 A and an average current of 630 A.

In the rf power extraction unit, average beam energy is maintained at 10 MeV by 3 100-kV induction cells per 1-m section that restore the 190 MW of power extracted in the rf output structure. The synchrotron period (particle rotation in the rf bucket) in the extraction unit is approximately 30 m. The rf output structures are detuned to compensate for bunch lengthening effects. However, the shorter synchrotron wavelength and closer spacing of rf output structures should improve longitudinal stability relative to the TBNLC design.

Transverse Beam Instabilities

The beam dynamics for the low frequency, 2-4 GHz, transverse instability due to beam interaction with the induction acceleration gaps, should be the same as in the TBNLC. Landau damping from energy spread will suppress this instability. However, the lower emittance required for
the RK-CLIC drive beam may require reducing the transverse impedance of the induction gap.

The high frequency, ~40 GHz, transverse instability due to higher order modes in the rf output structure, is a more difficult problem. There are twice the structures, and their transverse impedance is expected to be greater with respect to the TBNLC design. For the TBNLC, it was necessary to use the Betatron Node Scheme [3]. This scheme will remain valid for RK-CLIC where the structures are spaced at half Betatron wavelengths. The total effect should lead to an instability growth similar to that for the TBNLC, but perhaps requiring a higher tolerance on focusing field errors.

RF Output Structure Design

An illustration of the proposed RK-CLIC rf output structure is shown in Fig. 2. Direct scaling is geometrical.
the third stage consists of a 0.84-m long, water-filled Blumlein line. The first two stages use Strontium-Titanate capacitors. The long charge time of the first stage allows the use of a solid state system for the initial triggering.

The advantage of this magnetic compressor system is that it is totally solid state. It should have high-reliability, long lifetime, good efficiency, and be capable of kHz operation. A drawback of the system is that it is difficult to adjust the voltage wave shapes to obtain different accelerating gradients. Fast correction circuits interspersed in the system could be used to correct for errors.

System Efficiency

Where possible, comparable efficiencies for similar components with conventional klystrons or the TBNLC are used. We have based estimates on current technology.

(1) DC Power Supplies – Conventional 60 Hz 3 phase full wave rectifier with filter supplies will be used. Estimated efficiency is 93%.

(2) Command Resonant Charging (CRC) System – A solid state CRC system with estimated efficiency is 96%.

(3) Pulsed Power Modulator – Magnetic compression power losses are due primarily to three components, core losses, ohmic losses in the Blumlein water, and capacitors. Losses due to the cooling system are included under auxiliary power. Core efficiencies are given in Table 1. Assuming the same ratio between the outer and middle conductors radii as between the middle and inner, the energy loss in the water can be expressed as:

\[ U_L = \frac{240 \pi L V_o I_o \Delta t}{\rho V_r^2} \]

\[ L \] is the length (cm) of the Blumlein, \( V_o/I_o \) is the applied voltage (V)/current (A) to the load, \( \rho \) is water resistivity (\( \Omega \)-cm), \( V_r \) is relative permittivity, and \( \Delta t \) is charging time. In our design, \( L = 84 \) cm, \( V_o = 25 \) kV, \( I_o = 17 \) kA, \( V_r \) is 80, \( \rho = 8 \) M\( \Omega \)-cm and \( \Delta t = 250 \) ns for an energy loss of 0.094 J. The efficiency of the capacitors is estimated at 98%. Total estimated efficiency is 92%.

(4) Induction Cells – As described above, the cell efficiency should be about 65% for 50 ns pulses.

(5) Drive beam (pulse fall time) – As in the TBNLC, we plan to utilize the rise time of the current pulse. As an estimate of the energy to drive the core during the fall time, we allowed 300 A core current (average core current used for induction cell losses) times 20 ns fall time times one half of 100 kV or 0.3 J. This amount also includes the 0.1 J stored in the gap capacitance. Thus, actual losses during the fall time not previously accounted for is only 0.2 J giving an efficiency of 94%.

(6) Drive beam to rf – The conversion losses of drive beam to rf power are due to losses at the front of the relativistic klystron, primarily in the chopper, and residual beam power lost in the dump. This will be the same as for the TBNLC design, about 90%.

(7) Auxiliary power – This miscellaneous category accounts for losses in systems such as cooling fluids, vacuum, etc. These losses are estimated to be 80 kW. At 600 Hz this represents an efficiency of 0.96.

To summarize the estimated efficiencies:

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supplies</td>
<td>0.93</td>
</tr>
<tr>
<td>CRC</td>
<td>0.96</td>
</tr>
<tr>
<td>Modulator</td>
<td>0.92</td>
</tr>
<tr>
<td>Induction cells</td>
<td>0.65</td>
</tr>
<tr>
<td>Drive beam (fall time)</td>
<td>0.94</td>
</tr>
<tr>
<td>Drive beam to rf</td>
<td>0.90</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>0.96</td>
</tr>
<tr>
<td>Total wall plug to rf efficiency</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Summary

A preliminary study for a 30 GHz linear collider using the CLIC high-gradient linac and scaling of the relativistic klystron (RK) used in the TBNLC design was performed. The result was positive with an estimated wall plug to rf power efficiency of 43%. The rf to beam efficiency for the CLIC parameters used is 67% for a total efficiency of 29%. No attempt was made to optimize parameters for the combined rf power source/CLIC, e.g. gradient, and pulse length. However, increasing the pulse length could substantially improve the efficiency of the (RK) while also improving the efficiency of rf to beam conversion.

A very approximate costing study was performed. The cost of the 30 GHz RK-CLIC is practically the same as for the 11.4 GHz TBNLC. Savings due to the shorter pulse length and reduced energy per pulse are balanced by the additional cost of doubling the number of output structures.

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References