SHORT RF PULSE LINEAR COLLIDER

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Abstract

In general, a high gradient is desirable for future linear collider designs because it can reduce the total linac length. More importantly, the efficiency and the cost to sustain the high gradient should also be considered in the optimization process of the overall design. In this article, we explore the parametric territory of short rf pulses, high group velocities, high frequencies, high gradients, etc., that may lead to an affordable high energy linear collider.

INTRODUCTION

Ongoing efforts toward a TeV scale electron-positron linear collider from the International Linear Collider (ILC) and Compact Linear Collider (CLIC) teams are well established. Both proposed machines work at frequencies in the microwave range. The ILC, which uses superconducting cavities, is designed to operate with an rf pulse length of 1.5 ms and accelerating gradient ~35 MV/m. CLIC, based on a room temperature Two-Beam Accelerator (TBA) scheme, chooses the rf pulse length of 240 ns and the loaded gradient of ~100 MV/m. Meanwhile, futuristic high energy machines using plasma or laser based wakefield acceleration schemes are emerging, where accelerating gradients at the GV/m level have been demonstrated in various experiments. However, alternative designs of the high energy machine beyond the Large Hadron Collider (LHC) era are still attractive and meaningful, in particular, because history has shown that a good design may not lead to a practical machine due to its cost and other factors.

Although the physics behind rf breakdown has not yet been fully understood, observations in extensive experiments reveal that the rf breakdown threshold in accelerating structures increases while the rf pulse length decreases [1]. In present room temperature high gradient accelerator designs, ~150 MV/m gradient with a pulse length in the range of 200-400 ns is usually the limit of normal operations. In addition, rf power sources on the order of ~GW are required to power accelerating structures to achieve tens of hundreds of MV/m, which implies a new type of power generation other than the klystron is needed. Due to the simplicity of manufacture and the expected high breakdown threshold, a dielectric-based, short pulse (~20 ns), high gradient (~250 MV/m) traveling wave TBA is a good candidate to meet the requirements for future high energy machines: high efficiency, low cost and compact size, if the related technologies can be demonstrated.

One common concern related to the short rf pulse accelerator concept is the rf overhead, which is defined by the ratio of the rf transient time (i.e. the filling time in a traveling wave accelerator and the rise/fall time of the rf pulse) over the total rf pulse length in one rf pulse. Rf overhead is directly linked to the rf-to-beam efficiency as shown in Eqn. (1),

$$\eta_{rf-beam} = \frac{I_{beam} E_{load} L_s}{P_{rf}} \times \frac{T_{beam}}{T_{rf}} . \qquad (1)$$

A small rf overhead has a significant contribution to enhancing the rf-to-beam efficiency and hence the overall machine efficiency. In order to achieve a competitive rf-to-beam efficiency, a few strategies have been considered in a short pulse collider design: 1) using two beam acceleration scheme in the main linacs to avoid the slow rise time of klystrons; 2) using broadband accelerating structures; 3) design of the main linac with a relatively large group velocity and relatively short length to reduce the filling time; 4) design of the main linac with a relatively high frequency and optimal beam loading to improve rf-to-beam efficiency. Figure 1 shows the rf pulse structure we proposed in a 26 GHz short pulse TBA collider, which has a 9 ns filling time (~30 cm long accelerating structure and group velocity of ~11% of speed of light) and 3 ns of rf rise/fall time, resulting in 16 ns beam time over a total 28 ns rf pulse length (T_{beam}/T_{rf}=57.1%).

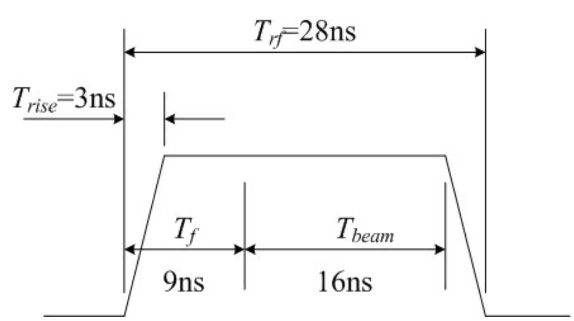

Figure 1. The 26 GHz rf pulse envelope for the short pulse TBA concept. A broadband and high group velocity (10%c) structure is needed for the fast rf rise and filling time.

SHORT PULSE COLLIDER

The proposed 3-TeV linear collider scheme uses a modular design (for details refer to [2]). A simplified layout of is shown in Fig. 2 (Positron generation and final beam delivery are not discussed in this article). It consists of ten 150 GeV stages in one side of machine. Each 150 GeV stage is made up of fifty discrete 3 GeV modules sharing one drive beam source, which makes it look like the CLIC scheme except for a few critical differences. First, in each 150 GeV stage of the proposed

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short pulse TBA scheme, 1000 (=50×20) short (~24 ns) micro drive pulses pass through 50 modules with a local beam pulse repetition rate of 20 (also representing a 20 5 µs-long macro bunch train. Each module provides a 3 GeV gain, which adds up to 150 GeV after 50 modules. Overall, these 1000 micro drive beam pulses, organized by 20 repetitive 5 µs long macro bunches, form a 100 µs giant beam pulse. The machine repetition rate is 5 Hz.

Second, to match the local beam pulse repetition rate of 20, the main beam consists of 20 short beam pulses in the same 100 µs period of time. The main beam current inside a pulse is set at 6.5 A, which is 0.5 nC per bunch, one bunch per 2 rf cycles. The purpose of introducing the local drive beam repetition rate is to increase the average beam current so that it can develop a beam power comparable to the long pulse design.

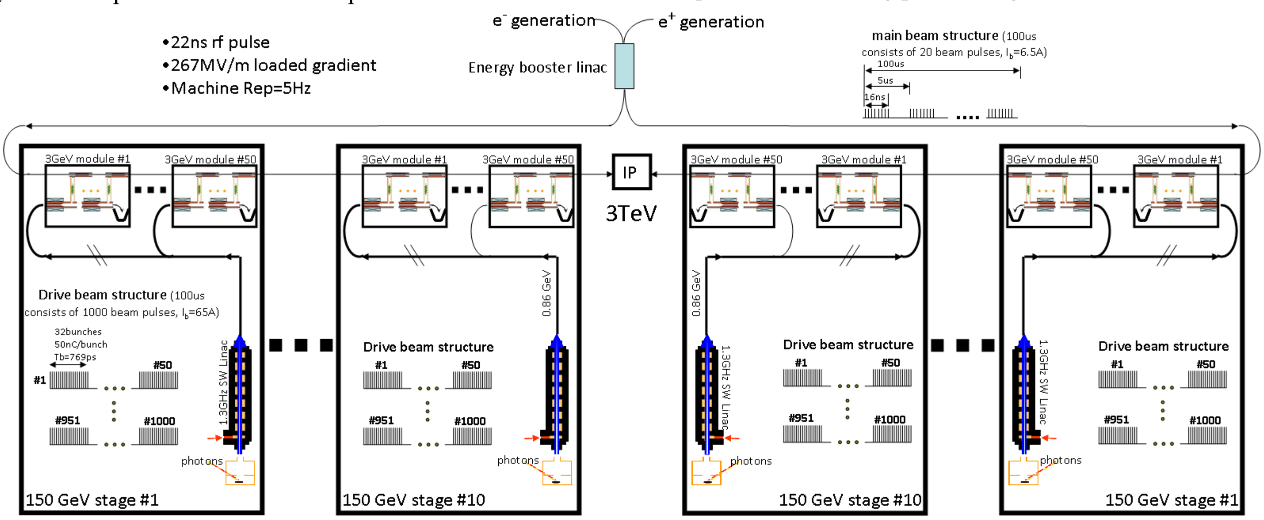

Figure 2: The conceptual layout of Argonne Flexible Collider.

Another obvious difference from the CLIC scheme is that the drive beam in this short pulse scheme is generated by a 1.3 GHz rf photoinjector in each 150 GeV stage with a high QE cathode, which can provide 50 nC/bunch with a bunch separation of 769 ps (32 sequential bunches form a ~24 ns micro drive pulse). At last, to achieve a high rf-to-beam efficiency in the main linacs under the short rf pulse condition, we choose a high frequency (26 GHz), high group velocity (~11% c), and dielectric based structure (broadband rf coupling), which in turn provides ~270 MV/m gradient (with the assumption of no breakdowns at this level in a 20 ns pulse duration), ~9 ns filling time, and ~3 ns rise time. Table 1 summarizes some preliminary design parameters. It should be pointed out that all parameters presented in the table are subject to change in future optimizations.

To some extent, the wall plug efficiency has become as important a factor as the luminosity and cost in considering the next generation linear collider design. Major sub-efficiencies in the power flow chain used to calculate the overall efficiency include the efficiency from the wall plug to power supplies and then to the klystrons' rf output, the rf-to-drive beam efficiency, the efficiency of the wakefield power extraction, and the rf-to-main beam efficiency. Here we consider a very rough estimate. The calculation starts from the final main beam power, 31.2 MW, from the parameter list in Table 1.

Revisiting Fig. 2, the main beam consists of twenty 16 ns long micro bunches during the period of a 100 µs giant drive beam pulse. Each 16 ns micro-bunch has 208 individual bunches with 0.5 nC in each. These 208 bunches are distributed every two 26 GHz rf cycles, corresponding to 6.5A beam current inside a microbunch.

Table 1: Some preliminary design parameters of the ANL Flexible Linear Collider (the informal name for the 3-TeV short pulse linear collider.)

Parameters	Value
Main linac frequency	26 GHz
Drive linac frequency	1.3 GHz
Main linac loaded gradient	267 MV/m
Main beam current (in pulse)	6.5 A
Machine repetition rate	5 Hz
Average drive beam current (one side)	80 mA
Average drive beam power (one side)	68.8 MW
Average main beam current (one side)	10.4 µA
Average main beam power (one side)	15.6 MW

The loaded gradient of the main linacs is 267 MV/m, calculated from the 1.264 GW input rf and 6.5 A beam loading. Each main accelerating structure is 0.3 m in length. Plugging these numbers into Eqn. 1, 26% rf to main beam efficiency is obtained. Calculating backward, 120 MW of rf input to the main linacs is obtained as well. With the assumption of 5% rf transport loss, the average output power from power extractors is ~126 MW. 137.6 MW of average drive beam power can be obtained similarly from the beam parameters. In every 150 GeV stage, the drive beam is boosted to 0.86 GeV through a series of L-band standing wave linacs before the entrance to each 3 GeV module. The L-band high coupling coefficient drive beam energy booster has been studied

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numerically. 86% rf to drive beam efficiency can be achieved [2]. Therefore, the rf power from the klystrons is 160 MW. For simplicity, 55% efficiency of AC to rf output of the klystron gallery (including klystrons, modulators, and accessories) is assumed; from this it can be inferred that 302 MW power is being supplied to the klystron gallery. Before going back to the wall plug, we use the same power consumed in main beam injection, magnets, services, infrastructure, and detector, etc. as that of the CLIC 3-TeV design [3] to complete the power flow chain, with the result that 431 MW AC power from the wall plug is estimated to generate 31.2 MW beam power, a total efficiency of 7.2%.

A PROTOTYPE MODULE

A 26 GHz short pulse two beam accelerator prototype module is currently under development. The power extractor which produces the 20 ns high power rf pulse was constructed and tested a few years ago [4]. Design and fabrication of the accelerator part (the 26 GHz dielectric accelerator) was completed and is ready for the bench evaluation. Its major parameters are summarized in Table 2.

Table 2: Parameters of 26 GHz Dielectric Loaded Accelerating Structure

Parameters	Value
ID / OD of dielectric tube	3 mm /5.026 mm
Dielectric constant	9.7 (Alumina)
Loss tangent	1×10^{-4}
Effective length of dielectric tube	100 mm
Shunt impedance of TM_{01} mode	50.44 (MΩ/m)
Group velocity	0.1115c
R/Q of TM_{01}mode	21983(Ω/m)
Q of TM_{01} mode	2295

Simulations were performed of a complete accelerating structure (Fig. 3a). >400 MHz bandwidth is reached in the simulation. The length of the structure was supposed to be 300 mm to match the power extractor. However, for this proof-of-principle structure, we choose 10 cm as the effective length to reduce machining difficulties. Shown in Fig. 3d, the single piece dielectric structure eliminates dielectric breakdown at the joints. The dielectric tube has two flared ends to match the impedance, which is critical to achieve the broad passband required for short pulse high gradient acceleration. The alumina tube was coated with 100 μm thick sputtered copper on the outer surface (Fig. 3b). We finished a straightforward engineering design of the 26 GHz short pulse DLA structure. Shown in Fig. 3b, the same length of circular waveguide will house the metallized dielectric tube. The position of the dielectric insert will be held by special designed gaskets, which have a slightly reduced inner diameter compared to the flange openings. A pumping port at the center of the copper housing will provide sufficient vacuum pumping. Two rf couplers were designed and fabricated as well (see Fig. 3c).

The complete two beam module is planned to be tested at Argonne Wakefield Accelerator facility [5] where a 75 MeV high current drive beam and a 15 MeV witness beam will be available as early as the end of 2012. In principle, >500 MW 26 GHz rf pulses are expected to be generated and fed into the 26 GHz DLA structure; an accelerating gradient in excess of 200 MV/m can be established, which can boost the witness beam energy from 15 MeV to 35 MeV in 10 cm.

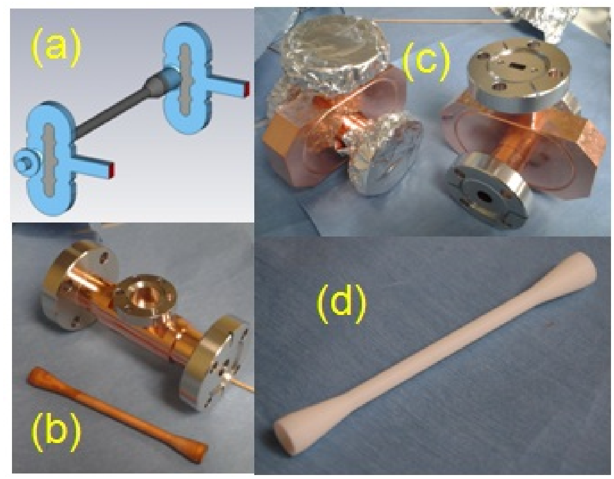

Figure 3. a) Design of the 26 GHz short pulse dielectric accelerator; b) Dielectric accelerator and metalized alumina tube; c) Two 26 GHz couplers; d) The alumina tube prior to metallization.

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