STUDY OF A TEV LEVEL LINEAR COLLIDER USING SHORT RF PULSE (~20NS) TWO BEAM ACCELERATOR CONCEPT*

C. Jing#, A. Kanareykin, S. Antipov, P. Schoessow, Euclid Techlabs LLC, Solon, OH 44139, U.S.A.
M. Conde, J. G. Power, W. Gai, ANL, Argonne, IL 60439, U.S.A.

Abstract

In a general sense, a high gradient is desirable for a TeV level linear collider design because it can reduce the total linac length. More importantly, the efficiency and the cost to sustain such a gradient should be considered as well in the optimization process of an overall design. We propose a high energy linear collider based on a short rf pulse (~22ns flat top), high gradient (~267MV/m loaded gradient), high frequency (26GHz) dielectric two beam accelerator scheme. This scheme is a modular design and its unique locally repetitive drive beam structure allows a flexible configuration to meet different needs. Major parameters of a conceptual 3-TeV linear collider are presented. This preliminary study shows an efficient (~7% overall) short pulse collider may be achievable.

SHORT RF PULSE ACCELERATION

Ongoing efforts toward a TeV scale electron-positron linear collider from the International Linear Collider (ILC) and Compact Linear Collider (CLIC) teams have been well established. Both proposed machines work at frequencies within microwave range. The ILC, which uses superconducting cavities, is designed to operate with the rf pulse length of 1.5ms and according gradient ~35MV/m. And the CLIC, which is based on the room temperature Two-Beam Accelerator (TBA) scheme, chooses the rf pulse length of 240ns and the loaded gradient of ~100MV/m. Meanwhile, futuristic high energy machines using plasma or laser based wakefield acceleration schemes are emerging, where the accelerating gradient in GV/m level has been demonstrated in various experiments. However, alternative designs of the high energy machine beyond the Large Hadron Collider (LHC) era 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 been fully understood yet, observations in extensive experiments reveals 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 tens of hundreds MV/m level, which implies a new type of power generation other than 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 rf transient time (i.e. filling time in a traveling wave accelerator and rise/fall time of the rf pulse) over total rf pulse length in one rf pulse. Rf overhead is directly linked to the rf-to-beam efficiency as shown in Eqn. (1),

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

A small rf overhead has a significant contribution to enhance the rf-to-beam efficiency which then 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 mina 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 26GHz short pulse TBA collider, which has a 9ns of filling time (~30cm long accelerating structure and group velocity of ~11% of speed of light) and 3ns of rf rise/fall time, resulting in the 16ns beam time over total 28ns rf pulse length (T_{beam}/T_{rf}=57.1%).

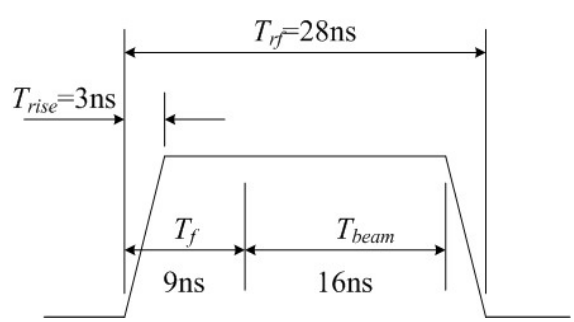

Figure 1: The 26GHz rf pulse envelope for the short pulse TBA concept. A broadband and high group velocity (10%c) structure is needed for the fast rf rise and filling time.

*Work supported by the Department of Energy SBIR program under Contractor #DE-SC0004320.
#jingchg@hep.anl.gov

SHORT PULSE COLLIDER

The proposed 3-TeV linear collider scheme uses a modular design (details refer to [2]). A simplified layout of is shown in Fig. 2 (Positron generation and final beam delivery are not discussed in the article). It consists of ten 150GeV stages in one side of machine. Each 150GeV stage is made up of fifty discrete 3GeV modules sharing with one drive beam source, which makes it look like the CLIC scheme except for a few critical differences. Firstly, in each 150GeV stage of the proposed short pulse TBA scheme, 1000 (=50×20) short (~24ns) micro drive pulses go through 50 modules with a local beam pulse repetition rate of 20 (it represents 20 5μs-long macro bunch train as well). Each module provides 3GeV gain, which adds up to 150GeV after 50 modules. Overall, these 1000 micro drive beam pulses, which is organized by 20 repetitive macro 5μs long macro bunches, form a 100μs giant beam pulse. On top of it, machine repetition rate is 5Hz. Secondly, to match the local beam pulse repetition rate of 20, the main beam consists 20 short beam pulses in the same 100μs period of time. The main beam current inside a pulse is set up at 6.5A, which is 0.5nC per bunch, one bunch per 2 rf cycles. The purpose to introduce the local drive beam repetition is to increase the average beam current so that it can make up a comparable beam power versus the long pulse design.

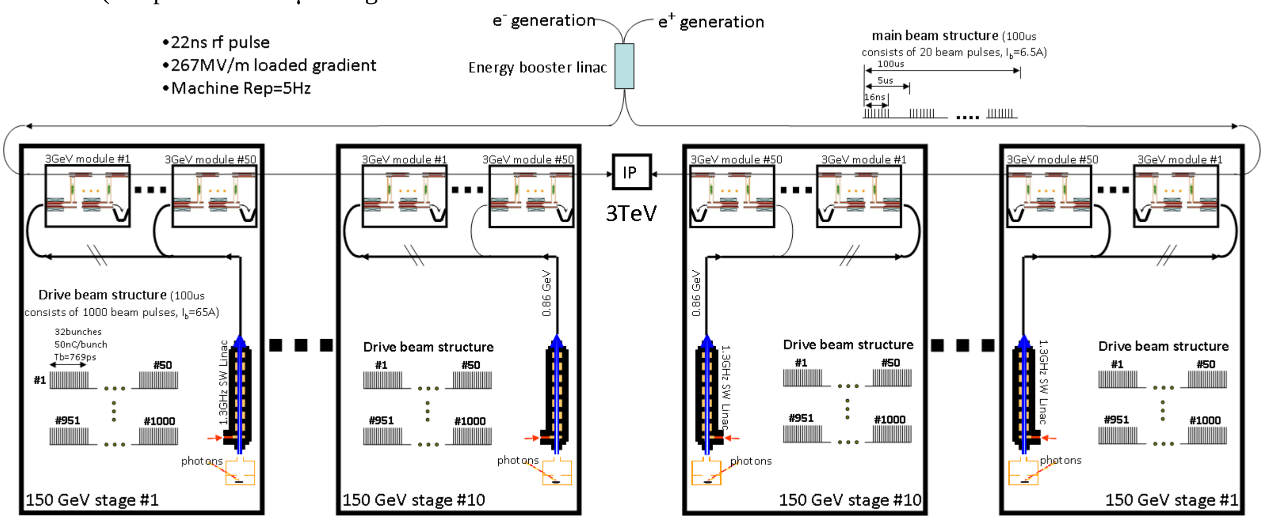

Figure 2: The conceptual layout of Argonne Flexible Collider.

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

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

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

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

Revisiting Fig. 2, the main beam consists of twenty 16ns long micro bunches during the period of a 100μs giant drive beam pulse. Each 16ns micro-bunch has 208 individual bunches with 0.5nC charge for each one of them. These 208 bunches are distributed every two 26GHz rf cycles, which is 6.5A beam current inside a micro-bunch. The loaded gradient of main linacs is 267MV/m, calculated from the 1.264GW input rf and 6.5A beam loading. Each main accelerating structure is 0.3m. Plugging these numbers to Eqn.1, 26% of the rf `to main beam efficiency is obtained. Calculating backward, 120MW of rf input to main liancs is obtained as well.

With assumption of 5% rf transportation loss, the average output power from power extractors is ~126MW. 137.6MW of average drive beam power, which is also listed in Table 1, can be obtained similarly from its beam parameters. In every 150GeV stage drive beam is boosted to 0.86GeV through series of L-band standing wave linacs before the entrance of each 3GeV module. The L-band high coupling coefficient drive beam energy booster has been studied numerically. 86% of the rf to drive beam efficiency can be reached [2]. Therefore, rf power from klystrons is 160MW. For the simplicity, 55% efficiency of AC to rf output of the klystron gallery (including klystrons, modulators, and accessories) is assumed that infers 302MW power being supplied to klystrons gallery. Before inversely 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. Eventually, 431MW AC power from the wall plug is estimated to generate 31.2MW beam power, which leads to 7.2% of total efficiency.

Details of a 3-GeV Module

As previous mentioned, the overall short pulse collider is a modular design. 1.5TeV electron side consists of 10 150GeV stages, and each stage can be broken into 50 3GeV modules. Detailed information of one 3GeV module is shown in Fig. 3. Every 3GeV module contains 38 0.3m-long two beam accelerator pair (wakefield power extractor and main accelerator). The total length of one module is 15m, which matches the time periodicity of micro drive bunches (100ns). The drive beam pulses are evenly distributed along a common transportation line in parallel but traveling with an opposite direction to the main beam so that the distance between drive bunches has to be twice the length of one accelerating structure to ensure the arrival time at the entrance of wakefield power extractor matching with the main beam. The wakefield power extractor is one to one mapped to the accelerating structure to satisfy the GW level rf power requirement of the main accelerating structure (Since the high group velocity of main linac design, it requires more rf power (>1GW) to build up the unloaded gradient ~300MV/m).

In every 3GeV module, the drive beam is 0.86GeV at entrance of the first wakefield power extractor. It loses 20.5MeV per every wakefield power extractor and provide 1.33GW rf output. The drive beam drops to 80MeV after 38 extractors and being dumped at the end of the 3GeV module.

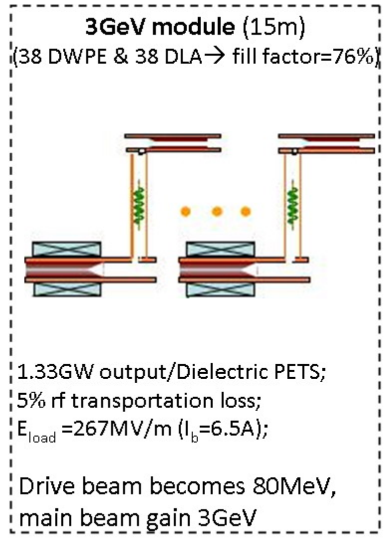

Figure 3: Schematic layout of a 3GeV module.

SUMMARY

We propose a high energy linear collider based on a short rf pulse (~22ns flat top), high gradient (~267MV/m of the loaded gradient), high frequency (26GHz) dielectric two beam accelerator scheme. The core of this short pulse scheme is to jump out of the ordinary structure breakdown regime and achieve much higher gradient by simply shortening the rf pulse length. The introduced local repetition rate of the drive beam and the overall modular design make the scheme more flexible and expandable to meet different needs. Preliminary parameter study shows a reasonable performance (competitive beam power and efficiency) of the 3 TeV collider based on the short pulse TBA concept if a few critical assumptions can be proved, such as: drive beam generation and acceleration; GW RF generation and high gradient demonstration in structures.

REFERENCES

[1] F. Wang, *et al*, *Proc. Advanced Accelerator Concepts: 14th Workshop*, edited by S. Gold and G. Nusinovich, (2010):280-285.
[2] C. Jing and W. Gai, WF-Note-239; http://www.hep.anl.gov/awa/links/wfnotes.htm.
[3] H. Braun, *et al*, CLIC-Note-764; http://cdsweb.cern.ch/record/1132079.